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Nonlinear, Incremental Structural Analysis of Zintel Canyon Dam

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Contents

Preface

This report provides an example of a nonlinear incremental structural analysis (NISA) performed for a recently constructed structure. The purposes of the report are to illustrate the process of implementing a NISA as described in ETL 1110-2-365 for a relatively simple project, make observations of the effectiveness of a NISA evaluation as applied to a constructed structure, and evaluate the suitability of existing guidance. The analyses were funded by Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Guidance Update Program.

The analyses were performed over a period of several months following the design and construction of Zintel Canyon Dam.

The report was written by Messrs. Robert E. Hollenbeck and Stephen B. Tatro, U.S. Army Engineer District, Walla Walla. Mr. Hollenbeck was responsible for performing the finite element analysis while Mr. Tatro provided all the data necessary to develop the time-history requirements implemented during construction and the time-dependent material properties used in the finite element model. Assistance with the ABAQUS software was provided by Mr. Chris A. Merrill, U.S. Army Engineer Research and Development Center (ERDC), Vicksburg, MS, and Mr. Barry D. Fehl, formerly of ERDC. Final review was provided by Mr. Jerry L. Foster, HQUSACE.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and COL James S. Weller, EN, was Commander.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
acre-feet	1233.489	cubic meters
cubic feet per second	0.02881685	cubic meters per second
cubic yards	0.07645549	cubic meters
Fahrenheit degrees	5/9	Celsius degrees or kelvins[1]
feet	0.3048	meters
gallons	0.003785412	cubic meters
inches	0.02540	meters
miles (U.S. statute)	1.609347	kilometers
pounds per square inch	6894.757	pascals
square miles	2589.998	square meters
tons (2000 lb)	907.1847	kilograms

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings use the following formula: C = (5/9) (F-32). To obtain kelvin (K) readings, use K = (5/9) – (F-32) + 273.15.

1 Introduction

Purpose

The U.S. Army Corps of Engineers, Civil Works, has been developing guidelines and procedures for determining thermally generated stresses resulting in construction of massive concrete structures. The original product of the research and development was documented in Engineer Technical Letter (ETL) 1110-2-324, Special Design Provisions for Massive Concrete Structures, which has since been superseded by ETL 1110-2-365, Nonlinear Incremental Structural Analysis of Massive Concrete Structures.

The U.S. Army Engineer District Walla Walla was commissioned to perform a thermal stress analysis of Zintel Canyon Dam located in southeastern Washington near Kennewick, WA. The goals in performing this study were to:

a. Perform a nonlinear, incremental, structural analysis (NISA) to evaluate the effects of temperature, Roller Compacted Concrete (RCC) material properties, and the subsequent volume changes on the cracking potential of Zintel Canyon Dam. The purpose of such an analysis was to evaluate costs and performance so that appropriate design features and requirements could be established. Obviously, since the dam was complete, no design modifications would be done. However, some observations of the effectiveness of such an evaluation could be made.

b. Demonstrate the implementation of the NISA process for an RCC structure and compare analytical performance with observed performance of the structure. In the process, evaluate the NISA method to provide recommendations on what measures may be implemented to make the process more serviceable. By performing a NISA of a current project at the District level, valuable insight would be gained on whether this analytical method is a suitable tool for designers and implementable at the District level.

c. Evaluate the suitability of the Corps of Engineers' guidance in performing nonlinear, incremental structural analyses for Zintel Canyon Dam. At the time the NISA was performed, the guidance was contained in ETL 1110-2-324. A new document, ETL 1110-2-365, has been published, but most of the procedures for performing a NISA remain the same.

Scope

This work was limited to the NISA evaluation of Zintel Canyon Dam. The analyses performed for the project were not intended to be comprehensive evaluations as described in the ETL, but abbreviated evaluations, more appropriate for a structure of this type and function. There are two reasons for this abbreviation. First, the structure is a simple gravity design, containing no contraction joints and impounding no permanent reservoir. Since transverse cracking of the structure poses no threat to the safety of the structure or to the public and does not impact the function of the project, a relatively simple analysis was sufficient. Second, the level of funding for this study was not sufficient to perform extensive analyses. Funding permitted only simple modeling and limited evaluations. However, the extent of analysis was sufficient to evaluate the thermal stress performance, to provide recommendations on District implementation of the NISA, and to evaluate the guidelines specified in the ETL.

Report

This report provides background on the development of finite element analyses for mass concrete structures which led to the development of the current procedures for performing thermal stress evaluations and Corps guidance on the subject. The NISA evaluation for Zintel Canyon Dam includes the details of performing the evaluation and the project-specific results, conclusions, and recommendations. Recommendations are provided on implementing a NISA evaluation and for modification of the guidance to make it more useful in application of the NISA process.

2 Background

Development of the NISA Process

Mass concrete structures are different from many concrete structures in that material properties have a significant effect on the state of stress in the structure. These material properties are not only dependent on the type and quantity of material, but on the age of the concrete, temperature of the concrete, and the state of stress of the material. Further, certain material properties exhibit nonlinear performance and somewhat unusual behavior at early ages. Consequently, definitive analyses of mass concrete structures require a very complex analysis procedure requiring the definition of many variables.

A further complicating factor is that most mass concrete structures, such as dams, are constructed over a long period of time. Consequently, thermal stresses develop during the construction phase and may be significantly affected by subsequent construction activities.

The evolution of an analysis package to adequately model these variables has been a long and tedious process. One of the earliest attempts to develop an analysis system was in 1966 during the design of Dworshak Dam. A finite element analysis package was developed, under contract, by researchers at the University of California, Berkeley. This system was likely one of the first such analysis tools ever developed. Over the years, the finite element analytical process has progressed to the point where many commercial vendors have provided quite sophisticated analytical tools for the evaluation of stress and strain in concrete structures. Unfortunately, most of these systems are general purpose computer codes that do not address the specific issues of the time-dependent behavior of mass concrete.

More recently, the Corps of Engineers has initiated the development of supplemental codes and techniques to enhance and refine the analytical process. The Corps selected for general use, ABAQUS, a general purpose finite element code. ANATECH Research Corporation, under contract to the Waterways Experiment Station (WES), now the U.S. Army Engineer Research and Development Center (ERDC), developed software subroutines to be used with the ABAQUS general purpose finite element code. These subroutines were designed to allow the user to input accurate, time-dependent and cracking material properties of concrete into the ABAQUS model.

ETL 1110-2-324 dated 30 March 1990, "Special Design Provisions for Massive Concrete Structures," was published, providing policy guidance to designers for execution of a NISA for the design of mass concrete structures.

Applicability of ETL 1110-2-324

The guidance provided by this ETL has been followed in the analysis and design of several structures. Most notable was the analysis of Lock and Dam 26 on the Mississippi River near St. Louis, Missouri, and the current design of Olmsted Locks and Dam on the Ohio River. Several concerns have been raised regarding the implementation of the ETL. The analytical process, as outlined in the ETL, is extremely comprehensive and expensive. Certainly, not all massive concrete structures require a NISA to be performed. The results of the study reported herein can be used to determine the applicability of the current ETL guidance for future projects that may or may not require a NISA be performed.

Project Description

Zintel Canyon Dam is a straight axis concrete gravity structure. The length of the structure is 520 ft across at the crest and the depth is 126 ft above the foundation at the deepest point. The structure is constructed of 70,600 cu yd of RCC. The outflow spillway is 160 ft wide with a crest 16 ft below the top of the dam. The spillway flows are contained by cast-in-place concrete training walls anchored to the RCC mass and RCC gravity training walls bordering the stilling basin. The dam, stilling basin, and stilling basin training walls are founded on basalt rock (see Appendix B for a more complete project description).

The project provides flood protection to the city of Kennewick, WA. It is located on Zintel Canyon, a 19-square-mile water course which threatens the city with winter snowmelt and summer thunderstorm events. The water course is otherwise a dry streambed. The structure will impound the 100-year flood for no more than 20 days. A self-regulating outlet provides reservoir drawdown at a controlled rate. The structure is designed to require no manned operations in the event of a flood.

After final excavation of the foundation, the rock surfaces were cleaned and covered with a wet-mix shotcrete and foundation concrete. RCC was placed in 12-in.-thick horizontal layers on and against these foundation surfaces. Interfaces of the RCC and the foundation concrete were bonded with a bedding mortar. Similarly, the RCC lift joints were fully bonded with the same bedding mortar. RCC placement began on 6 July 1992 and was completed on 15 October 1992. The 126 RCC lifts were placed in approximately 75 placing days during a 100-day period. In general, the process was to deliver the RCC to the dam on a conveyor. Front-end loaders received the RCC and transported it to the desired location. The RCC was spread with a small dozer and compacted with a vibratory roller.

3 Thermal Cracking Evaluation

General

The purpose of performing a thermal cracking evaluation for Zintel Canyon Dam was to determine the consequent cracking of the structure resulting from thermally generated volume changes. Since the evaluation was performed some time after the construction of the dam, actual conditions, such as ambient temperatures, RCC placing temperatures, and placing schedules were used in the model. However, additional laboratory work to characterize RCC materials was not done because of limited funds. This included creep properties, thermal properties, and tensile strain capacity. Instead, these material properties were estimated. In addition, the limited access to computer resources necessary to perform the analyses further limited the depth of the investigation.

ABAQUS Model

After developing the mesh for a two-dimensional transverse model through the spillway section, it became apparent that a three-dimensional model would become extremely large. Although the computer (CRAY Y-MP supercomputer) could handle the computational analysis during this study, the time required to execute such a model would have been extensive, due to the system workload. In addition, the geometry of the dam does not lend itself to easy input generation for ABAQUS and as a result, extensive efforts to generate the model would be required. A three-dimensional model would increase the cost of the study significantly beyond initial estimates. Because of these factors, the study was limited to two two-dimensional models.

Thermal analyses of this nature have most often been done using two-dimensional models. A two-dimensional transverse model usually gives good analytical results that can be used to predict cracks that propagate inward from the surface and cracks originating from the foundation. However, recent projects, most notably Upper Stillwater Dam, experienced significant cracking. These cracks propagate vertically from the foundation and are oriented perpendicular to the longitudinal axis. The Bureau of Reclamation performed a thermal analysis to predict the crack potential. They utilized a transverse,

two-dimensional model and a longitudinal model of a horizontal plane. Because of the magnitude of the cracks at the foundation/RCC interface, it was necessary to determine the suitability of a longitudinal model of a vertical plane for use in predicting crack potential. As a result, two two-dimensional models were analyzed. One model computed stresses resulting from a transverse model and the other computed stresses from a longitudinal model in a vertical plane.

While these two-dimensional models provide less accurate solutions than a three-dimensional model, the accuracy is appropriate considering the size of the project and available funding for the study. The limitation of the two-dimensional, longitudinal model is that it is assumed that symmetry exists on either side of the longitudinal plane, which is not the case. This assumption may cause a shifting of the thermal gradient from its actual location. In the case of the transverse model, the full section is modeled which more accurately models the thermal gradient. Figure 1 shows the location of the assumed two-dimensional plane through the dam. Thermal contours of both models shown in Figures 2-11 demonstrate a good correlation of peak temperatures between the two models.

Development of Input Data

Because RCC exhibits material characteristics similar to those of conventionally placed mass concrete, the analytical process for determining thermal gradients and stresses in RCC is practically the same. The analytical procedures have been well documented by previous analyses and authors and should follow the general guidance established in ETL 1110-2-324.

However, RCC construction generally occurs over a relatively short time frame with numerous lift joints (usually 1 to 2 ft in height). Conventionally placed mass concrete usually involves placements with lift heights of 4 to 7 ft with 5- to 7-day restrictions placed on form removal. The exposure and depth of each lift in conventionally placed concrete will generally define the limits of the number of steps necessary to perform the incremental analysis. In contrast, continuous placement of RCC on some projects has achieved four 1-ft-lift heights in 24 hr. In a 7-day period, RCC can achieve changes in elevation of 25 to 30 ft, depending on the project specifics and resultant production rates. Therefore, before a NISA can be performed for RCC, a comprehensive study of production rates must be completed in order to select time steps, the number of steps, and element mesh size. The results of the production rates, in combination with the element size, and parametric studies described in the following paragraph, will define the element mesh.

Model Details

The mesh sizes for the two models were established by the equation provided in the ABAQUS user manual and restated in ETL 1110-2-234. Results from this equation were found to be very restrictive on the element size. Instead,

a simple parametric study was performed to determine if a larger element size could be used without creating numerical instabilities in the thermal model. The results of the parametric study indicated that the maximum length of the element in the direction of heat flow could be 48 in. For both models, 48 in. was the maximum size of element used in any direction for a 6-hr time interval. A 6-hr time interval was chosen based on production rate of RCC and because it satisfied the maximum time interval required to compute early heat gain in the concrete. Results of the parametric study are shown in Appendix A.

Mesh size was then correlated with the RCC placement schedule of the dam and was designed to capture heat gains at the early ages of construction. Figure 1 represents a time history for construction and the analysis for the transverse and longitudinal models, respectively, as well as the initial conditions, boundary conditions, and input values used. Boundary conditions include the insulating effects of upstream precast facing panels, free surface convection, soil (rock) conditions, downstream stilling basin slab, and average daily temperatures for preconstruction, during construction, and postconstruction. Initial conditions include RCC placement temperatures and initial foundation temperatures. The user subroutine DFLUX was used, in conjunction with ABAQUS, to generate time-dependent heat fluxes for the thermal analysis. Parameters used in DFLUX included adiabatic heat gain (time and temperatures) for the RCC mix as well as initial placement times for each lift. Adiabatic heat gain curve is plotted in Figure 1.

Results

Results of the thermal analysis for both the transverse and longitudinal models are represented in contour plots in Figures 2 through 11, and time history plots of maximum nodal temperatures in Figures 12 and 13. The maximum temperature reported in the transverse model is represented by node 2330, Figure 12c, and in the longitudinal model by node 3213, Figure 13c. Maximum temperatures and temperature differential correlate well with predicted temperatures calculated by using approximate computational methods for Zintel Canyon Dam. As stated previously, effects of maximum heat gain between the two models were nearly the same. However, there is a notable difference in the rate of cooling. The two-dimensional elements do not have the capability to conduct heat in the out-of-plane direction. With convection being modeled along the top surface only, of the longitudinal model, the elements sustain a higher thermal gradient over a much longer period of time.

Discussion of stresses for both models should be limited to principal tensile stresses. However, software developed for plotting stress histories is only capable of plotting stress in orthogonal directions and for shear stresses. Because Zintel Canyon Dam normally has no pool and experiences a very short duration reservoir impoundment, cracking posed no concerns related to seepage. Of concern are the orientation of cracks that will compromise the stability of the structure.

A feature of the ABAQUS-based NISA that sets it apart from others is that it allows material properties and relationships to be user-defined. UMAT is the subroutine that provides a time-dependent cracking material model. The subroutine allows input of specific material properties and calibration of the model-predicted properties against actual observed material performance.

While some material testing had been done for Zintel Canyon Dam, extensive evaluation of time-dependent properties and creep performance had not been determined. Consequently, calibration of the UMAT material model could not be performed. The material model generated for Olmsted Locks and Dam was used except that the material constants were replaced with actual or estimated values for Zintel Canyon Dam RCC materials. This means that the UMAT predicted performance for Zintel Canyon Dam was based on Olmsted material relationships. No data were available to shift the relationship curves. Without actual data to calibrate the material model, changes would be arbitrary and not necessarily an improvement over using the Olmsted data. To perform a reliable NISA, these material properties need better definition. More complete definitions of the development of the modulus of elasticity and creep are critical to accurate results.

For smaller scale projects, standard relationships for a range of materials should be developed so that the analyst can select the performance relationship that most likely models the materials being evaluated. Only the larger projects will have the funding to perform a complete battery of laboratory evaluations. For the longitudinal model, the maximum principal stress occurred at the foundation/RCC interface at element 1796. Stress contours for the transverse model are presented in Figures 14-19. Stress contours for the longitudinal model are presented in Figures 20 and 21. Principal stress contours for the longitudinal model are shown in Figures 22-25. ABAQUS calculated a maximum principal stress of 715 psi which occurs during the cooling period when maximum temperature differentials occur. Earlier testing of the RCC mix indicated a 28-day tensile strength capacity of 200 psi. The 715-psi principal stress calculated is far in excess of the tested direct tensile capacity. This may be attributed to the fact that the analyses were performed using the original version of UMAT. That version contained inconsistencies which resulted in the cracking threshold to be computed in an unconservative manner. This inconsistency has been corrected in the current version of UMAT which was not available when this study began. However, newer versions of software available at ERDC have the capability to predict and plot direction and magnitude of cracks. Observations of the stress contours for the longitudinal model indicate higher stresses occur at the foundation interface and in the upper reaches of the abutment and at the spillway. This can be attributed to the temperature differential occurring between the exterior and interior elements and the rigidity of the foundation. At the time of year for postconstruction cooling, the average ambient temperature is decreasing causing a larger temperature differential from surface elements to interior elements. Time history stress plots of various points of high stresses observed in the contour plots for the transverse model are presented in Figures 26-32 and for the longitudinal model in Figures 33-40. The stress time histories presented in Figures 36 and 38 indicate that some cracking may have occurred.

Jumps in stress, as indicated in these plots, typically do not occur unless a crack has formed. Discussion of these results are presented below. Likewise, the transverse model predicted stresses that are higher than the limited cracking stress. The highest stress occurred at element 217 at the foundation/RCC interface. In addition, a region of high stress occurs along the downstream exposed face of the dam.

4 Discussion

A simple thermal analysis was done for the project during the design phase of the project. This analysis indicated that during the normal summer weather conditions at the site, the structure may crack at three locations. Two-crack locations were estimated to be located where the foundation changes from a horizontal surface at elevation 635 to the sloped abutments. The third crack was speculated to be in the center of the spillway. None of these cracks pose a threat to the stability of the structure since the orientation will be in the traditional upstream-downstream direction. In addition, since the dam is almost continuously dry, and channel flows carry a phenomenal silt load, this cracking of the structure is not of great concern. No additional expense was warranted in lessening the cracking potential by reducing the placing temperatures or by installing transverse joints.

Postconstruction inspections revealed one crack in the structure located high on the left abutment as a result of a slope change in the foundation. No other cracks are apparent. Less cracking has been observed because the restraint provided by the foundation is probably lower than full restraint assumed by the simple analysis.

Examination of the temperature history plots indicates that the longitudinal model cools at a much slower rate. The benefits of performing a longitudinal model are significant when time and costs are of concern for smaller projects, or projects of this type where certain cracking will not adversely affect the performance of the structure. However, in this case, the thermal gradients of the longitudinal model should be calibrated with the more accurate transverse model to produce nearly the same rate of cooling. This may become a significant factor in the analysis because:

- While cooling is at a slower rate than might be expected, this will cause volume changes and, hence, the maximum stresses to occur at a later age in the model. Since the higher stresses occur later in time, the aging modulus will be higher. Since the criteria for cracking are partially based on stress, the potential for cracking will be unconservative for this case.

- The thermal stresses are being applied at a later age; therefore, the effect of creep will play a less significant role in stress relaxation. This may be

conservative; however, as long as a large amount of effort has been expended to accomplish a material investigation, it would be prudent to spend the same amount of effort to calibrate the longitudinal model. This will ensure that the analysis will incorporate the more accurate creep data in the earlier time steps when cooling would be expected to cause higher stresses. Hence, the effects of stress relaxation due to creep will be incorporated into the analysis.

Calibrating the longitudinal model may be done by adjusting the thermal conductivity of different element sets, allowing for higher conductivity in the earlier time steps and reducing the conductivity in the later time steps where the convective surface plays a more significant role in cooling.

Examination of the stress history plots indicates stresses are still increasing as a result of decreasing ambient air temperatures. For both models the cooling period should, at a minimum, be applied until thermal stresses begin to decrease and attain a steady state. For this analysis the cooling period was 9 months for the transverse model and 3 months for the longitudinal model. Admittedly, this analysis fell short of predicting maximum stresses. However, review of the principal stress contours from the longitudinal model reveals high stress areas where cracking is likely to occur. One area is at the center of the spillway, the second, at the intersection of the spillway and nonoverflow section, and the third, in the upper reaches of the abutments. With the version of UMAT used for this study, it is difficult to predict where cracking will initiate first. However, where locations of high stresses occur, the model may be modified to depict the location of transverse joints if cracking is undesirable in those regions. Other conditions that affect the stress in the dam are the assumed foundation restraints. Both models include fully restrained boundary conditions at the RCC/foundation interface. By visual observations of the rock and postconstruction coring of the foundation, the assumed restraint conditions used in the model could be modified to provide a more flexible restraint condition or an adjusted foundation modulus. Before proceeding with any further analysis, the most recent version of UMAT should be used to include the redistribution of stress that occurs after cracking. For this study, no further calibration of the longitudinal thermal model was completed. This is mainly due to limited scope of the study and the fact that cracking is not of great concern for Zintel Canyon Dam.

5 Conclusions and Recommendations

Study Conclusions

Performance of the analysis leads to several conclusions and recommendations for subsequent steps to proceed with further evaluation of cracking. The first step would be to make the required adjustments in the foundation modulus and/or the restraint conditions. The model for Zintel Canyon Dam included the foundation in the stress analysis. Adjusting the foundation modulus to tested values would be more appropriate in this case. If the foundation conditions are modeled by the use of springs, the degree of restraint may be adjusted by softening or stiffening the spring constants. In the case of Zintel Canyon Dam, the foundation rock was highly fractured. Therefore, the degree of restraint provided by the concrete to rock interface may be less than fully restrained. However, unless sufficient data support softening the spring constants, the results of the stress analysis would be unconservative in this case. Secondly, the model can be modified by inserting a transverse joint at the midpoint of the spillway or at the corners of the spillway/nonoverflow intersection. Additional measures could include reducing the RCC placement temperature and mandating placement schedules to avoid hot seasons.

For Zintel Canyon Dam, considering the frequency of reservoir impoundment and the function of the structure, the observed cracking is well within acceptable levels for the project. There would be no benefit for implementing these measures.

The results of this NISA analysis were, in general, consistent with the results of the approximate thermal analysis performed during design of the project. Both indicate that cracking may occur in three areas. Based on that comparison and the observed performance of Zintel Canyon Dam and other RCC dams, the NISA for Zintel Canyon Dam provided no additional information to attain the desired objectives stated in the ETL. This statement is based on the fact that:

- Some cracking would be acceptable as long as structural stability is not compromised.

- Joints for control of cracking are not necessary for serviceability conditions since there is no permanent reservoir.

- Because of the combinations of the above, real cost savings have been achieved by maximizing production rates for placement of RCC.

- Unusual loadings, extreme loadings, or severe operational conditions do not exist.

This is not to say that a NISA should not be performed for RCC structures. Each structure is subject to unique conditions and loadings resulting in unique structural features. These factors are evaluated and developed by a team of responsible engineers who must determine the level of analyses and consultation necessary to obtain any of the desired objectives stated in the ETL. The ETL cannot provide guidance for all possibilities.

NISA Application Conclusions

Two conclusions were reached from this study:

a. *Conclusion 1.* This evaluation was performed over a lengthy period of time. The time period was much longer due to a start-stop approach employed for the study. Several problems were identified during this period that seem to be shortcomings of the current NISA process. Admittedly, some of the problems encountered were due to the protracted approach taken. A start-stop operation is rarely an efficient operation.

b. *Conclusion 2.* Accessing the CRAY computer provides a variety of problems. Remote access for field use of ABAQUS at this time is not possible because ABAQUS is currently site-licensed for use at ERDC. Districts preparing to embark on such a study will find it necessary to utilize ERDC personnel at ERDC or perhaps negotiate a contract with the ABAQUS owner (Hibbitt, Karlsson, and Sorenson Inc.) to allow the District access to ABAQUS via the ERDC CRAY. Our conclusion is, that while the CRAY may provide significant computing capability, the logistical problems to off-site users may provide more problems than solutions for off-site users.

There has been a tremendous amount of effort expended in developing NISA via ABAQUS and the user subroutines. The logical next step is to develop desktop software packages that would be beneficial to Districts with smaller projects requiring finite element analysis or with larger projects where preliminary two-dimensional modeling is necessary prior to embarking on a full-scale three-dimensional NISA. The CRAY-based software usage would then be reserved for those rare monumental projects. It is recommended that a micro-based version of this software be utilized for most applications.

A critical deficiency in the ABAQUS analytical package is the lack of graphic preprocessing and postprocessing routines. Adequate preprocessing would eliminate much of the input generation errors. Currently (January 1994), there is no interactive preprocessing capability. Further development of preprocessing and postprocessing routines should match formats provided by some of the more common processing routines currently being used by designers.

For these analyses, input to the user subroutines required changing the FORTRAN code to provide heat flux information, and creep and shrinkage characteristics corresponding to appropriate element sets. Although many engineers can decipher FORTRAN code, many involved in the work may not have produced any programs for years. This can be time-consuming and is a waste of effort in the design. A more appropriate means for entering data would be via batch files to the user subroutines as is currently permitted. UMAT is an extremely comprehensive subroutine that is the crux of the time-dependent stress analysis. Subsequent to this study, the capability for entering data to the user subroutine through a batch file was implemented.

Recommendations

For Districts to utilize ABAQUS in order to execute a NISA as part of the design process, and to achieve the stated objectives in the ETL, ABAQUS must be readily available to District designers. Without these labor-saving additions, ABAQUS use by designers outside of ERDC may never develop.

Wide usage by Districts will no doubt require sophisticated support services in the form of training and user support. This service is best provided by ERDC. Program orientation is recommended in the form of a periodic PROSPECT course on the use of the NISA/ABAQUS system. Furthermore, a staff member(s) must be available to service the ABAQUS system and provide user support. User support may range from troubleshooting user problems to working as part of the design team.

Future guidance concerning mass concrete should address whether performing a NISA is mandatory. Current guidance is unclear; i.e., a reader can either assume that a NISA is mandatory (ETL 1110-2-324 paragraph 7*a*) or that the need for such an investigation is subject to consideration (ETL 1110-2-324 paragraph 7*b*). It should be noted that a new ETL has been published, that incorporates updated information based on NISA's that have been performed by ERDC that may address these issues. The considerations for when to implement a NISA versus other less comprehensive analyses need to be developed and included in any comprehensive policy document.

Certain basic questions must be addressed prior to embarking on a NISA. These include:

- Why do a thermal study?

- Is a thermal study appropriate for this structure? If so, what level of analysis is necessary?

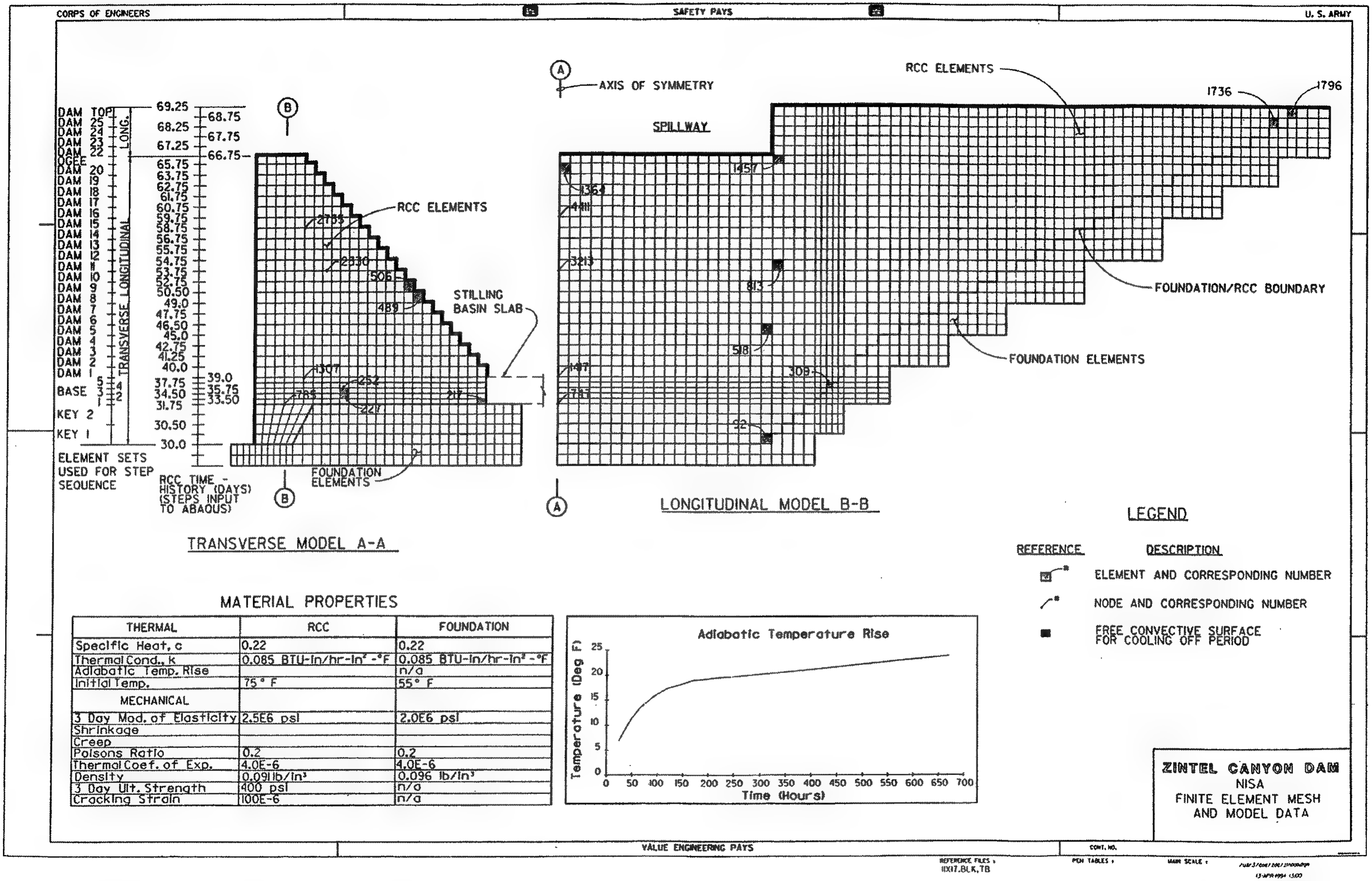
- What are the basic principles?

- How do I do a thermal study?

It is recommended that future documentation address these issues. The document should address the basic issues of the goals and desired objectives when performing thermal studies and supplemented with more specific information, for all levels of analyses.

Guidance in the ETL references acceptable bandwidths to be applied to the mechanical properties of the concrete for estimated data. There are several ways to generate reasonable estimates of these data at the time of the analysis. Further guidance, that would be beneficial, should reference other sources that contain the methodologies to estimate the data.

We concur with the recommendation of the ETL that the full intended benefit of a NISA requires the combined efforts of the structural designer, materials engineer, cost engineer, and the geotechnical engineer.



THERMAL	RCC	FOUNDATION
Specific Heat, c	0.22	0.22
Thermal Cond., k	0.085 BTU-in/hr-in² -°F	0.085 BTU-in/hr-in² -°F
Adiabatic Temp. Rise		n/a
Initial Temp.	75° F	55° F
MECHANICAL		
3 Day Mod. of Elasticity	2.5E6 psi	2.0E6 psi
Shrinkage		
Creep		
Poisons Ratio	0.2	0.2
Thermal Coef. of Exp.	4.0E-6	4.0E-6
Density	0.091 lb/in³	0.096 lb/in³
3 Day Ult. Strength	400 psi	n/a
Cracking Strain	100E-6	n/a

Figure 1. Finite element mesh and model data

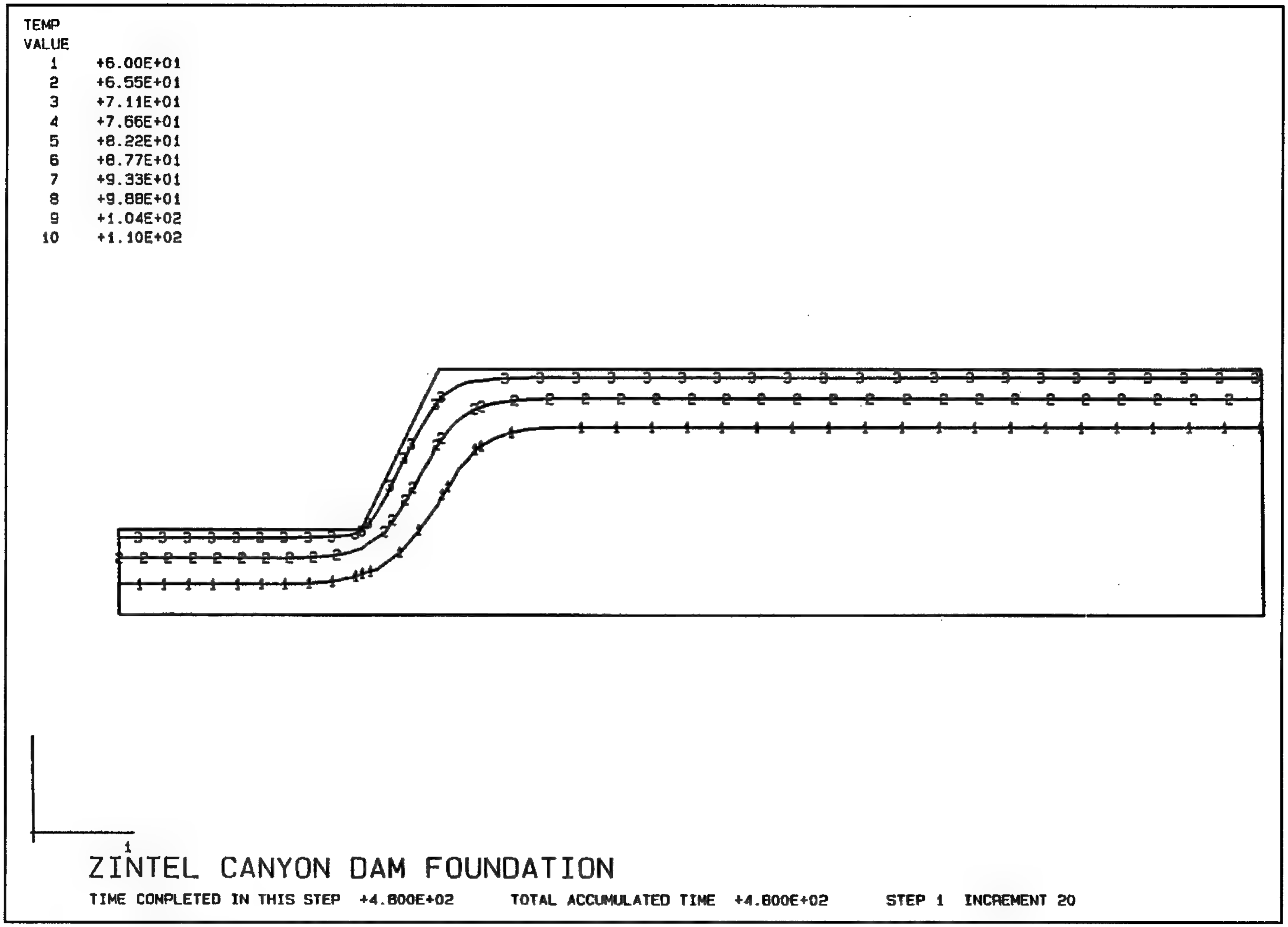


Figure 2. Temperature contours, transverse model, Zintel Canyon Dam foundation

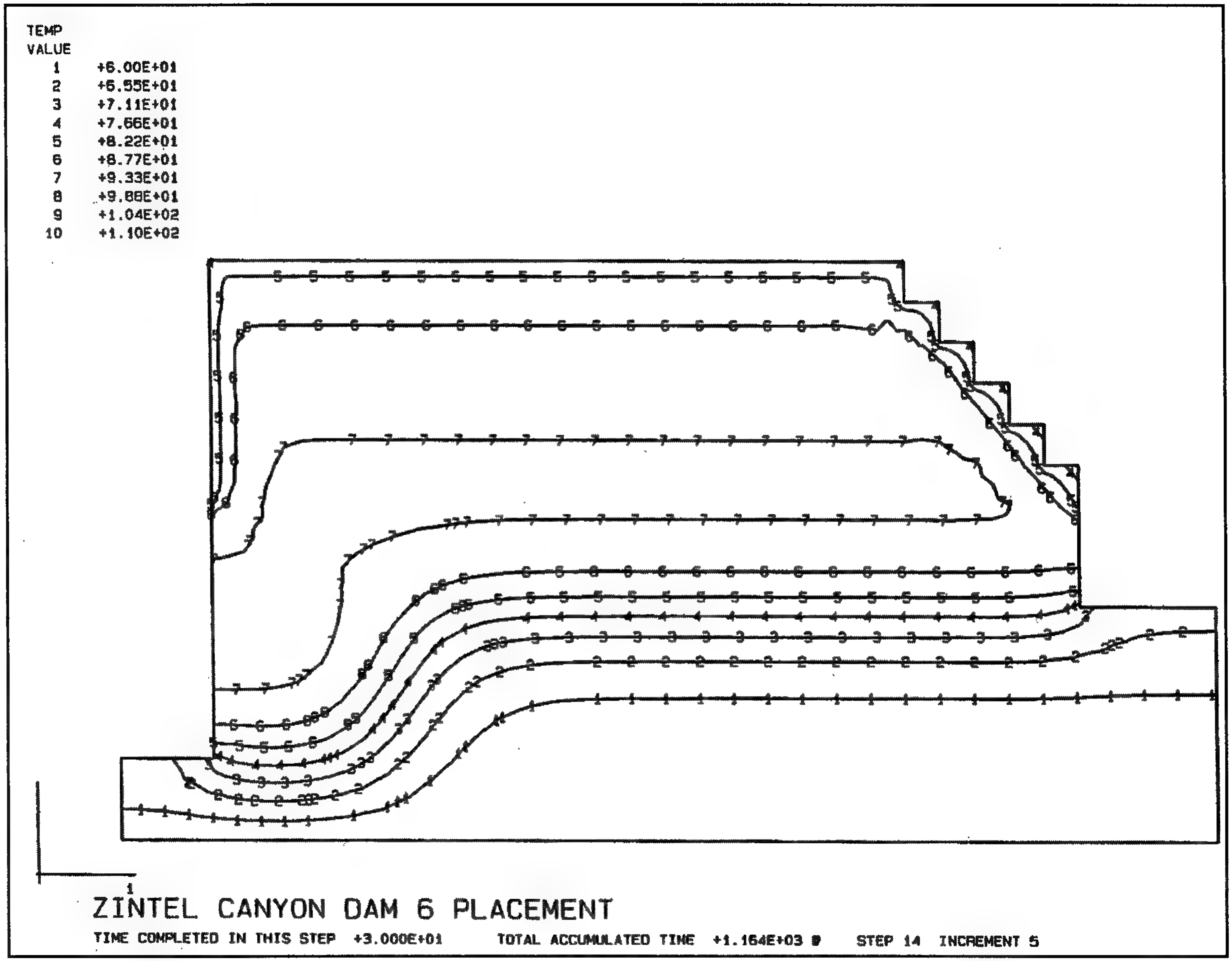


Figure 3. Temperature contours, transverse model, Zintel Canyon Dam 6 placement

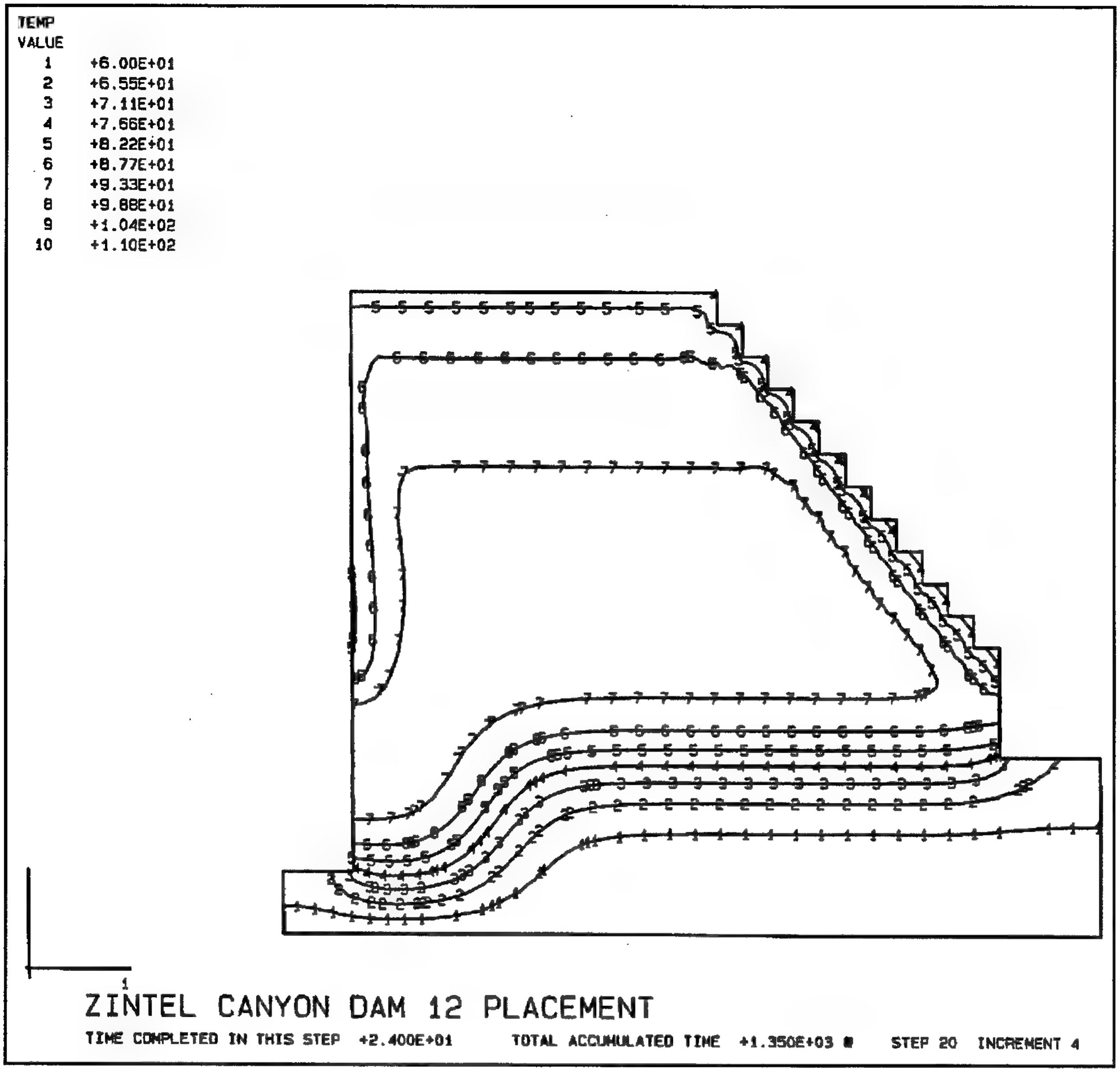


Figure 4. Temperature contours, transverse model, Zintel Canyon Dam 12 placement

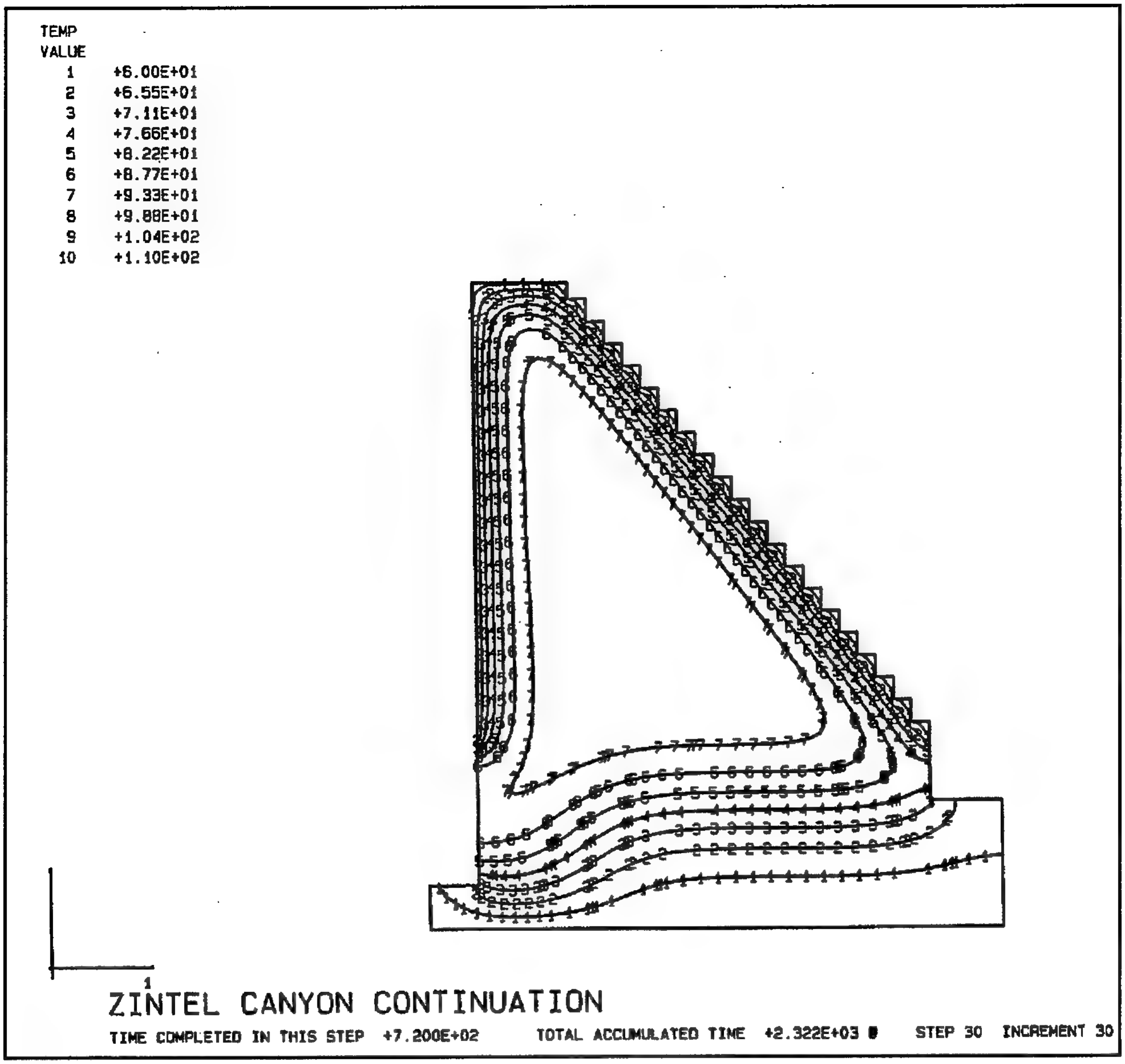


Figure 5. Temperature contours, transverse model, Zintel Canyon Dam continuation, step 30

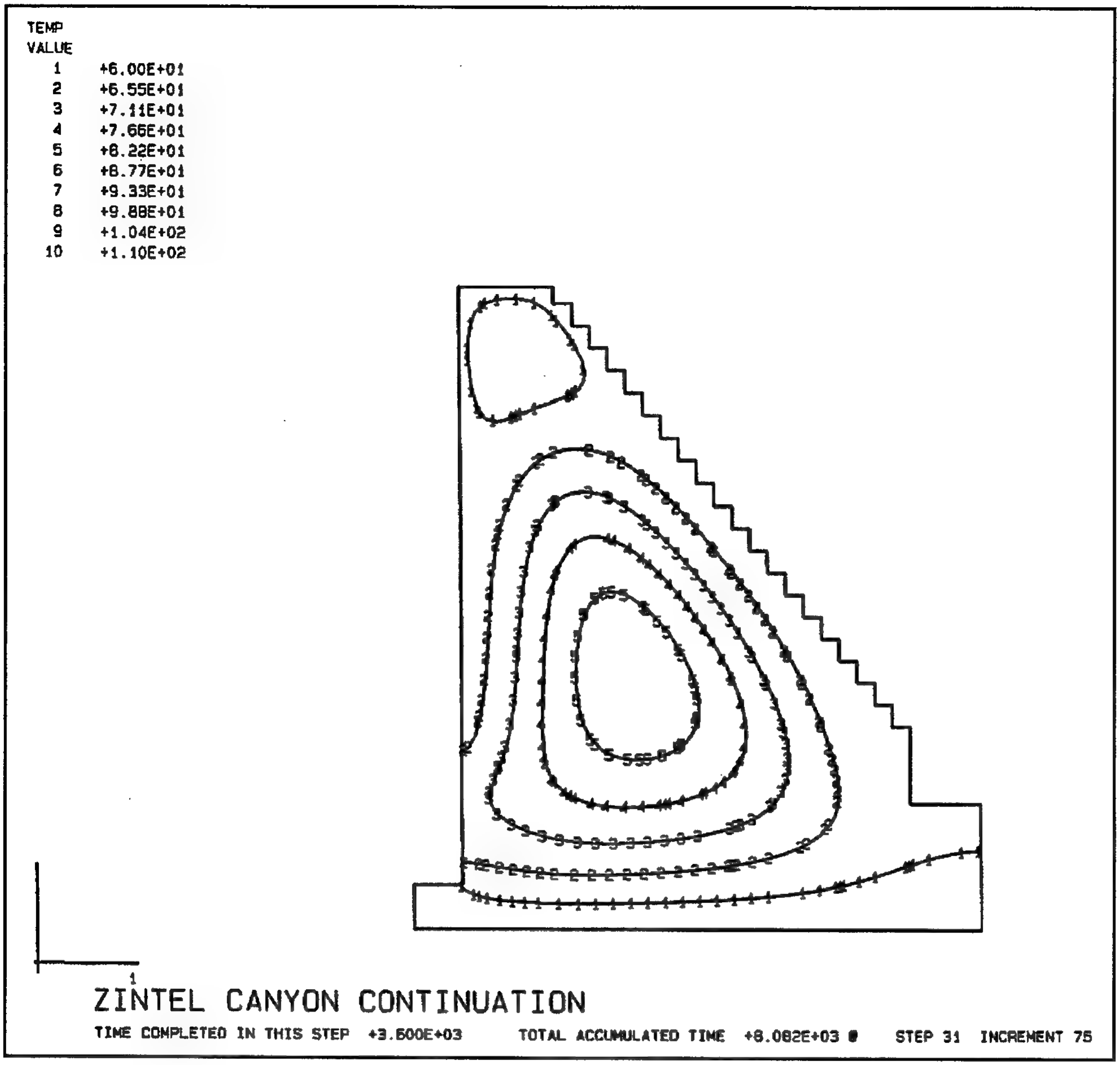


Figure 6. Temperature contours, transverse model, Zintel Canyon continuation, step 31

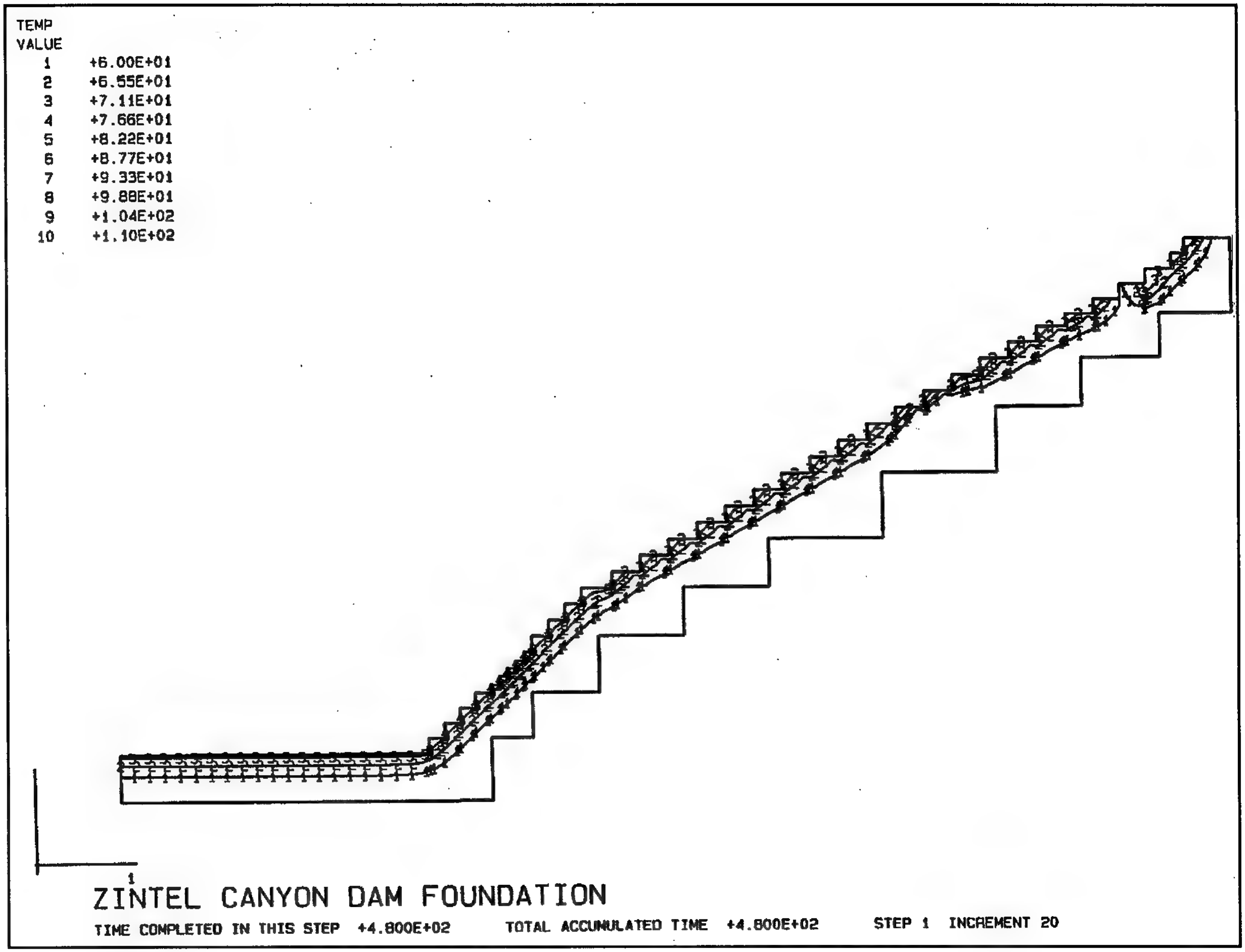


Figure 7. Temperature contours, longitudinal model, Zintel Canyon Dam foundation

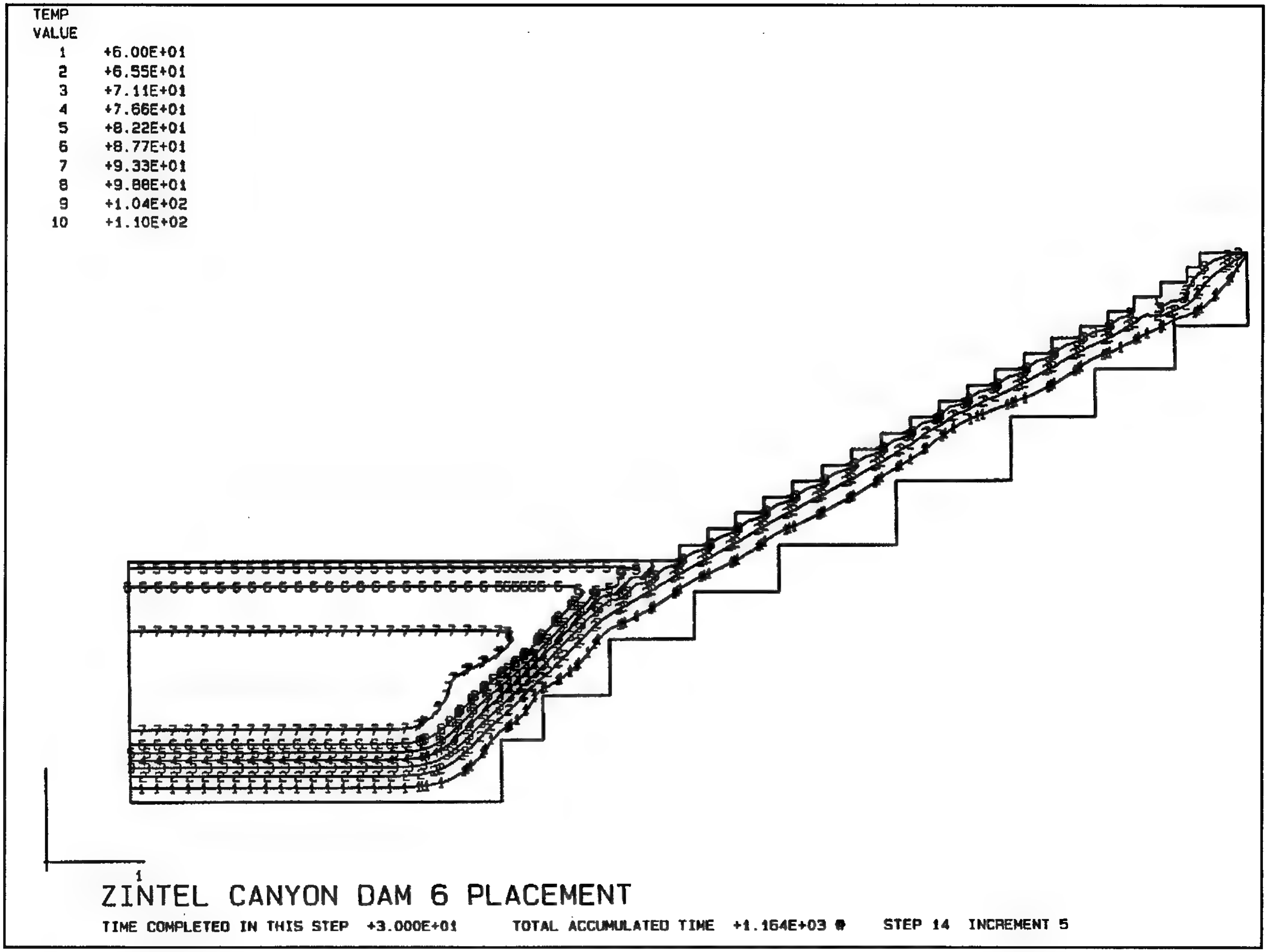


Figure 8. Temperature contours, longitudinal model, Zintel Canyon Dam 6 placement

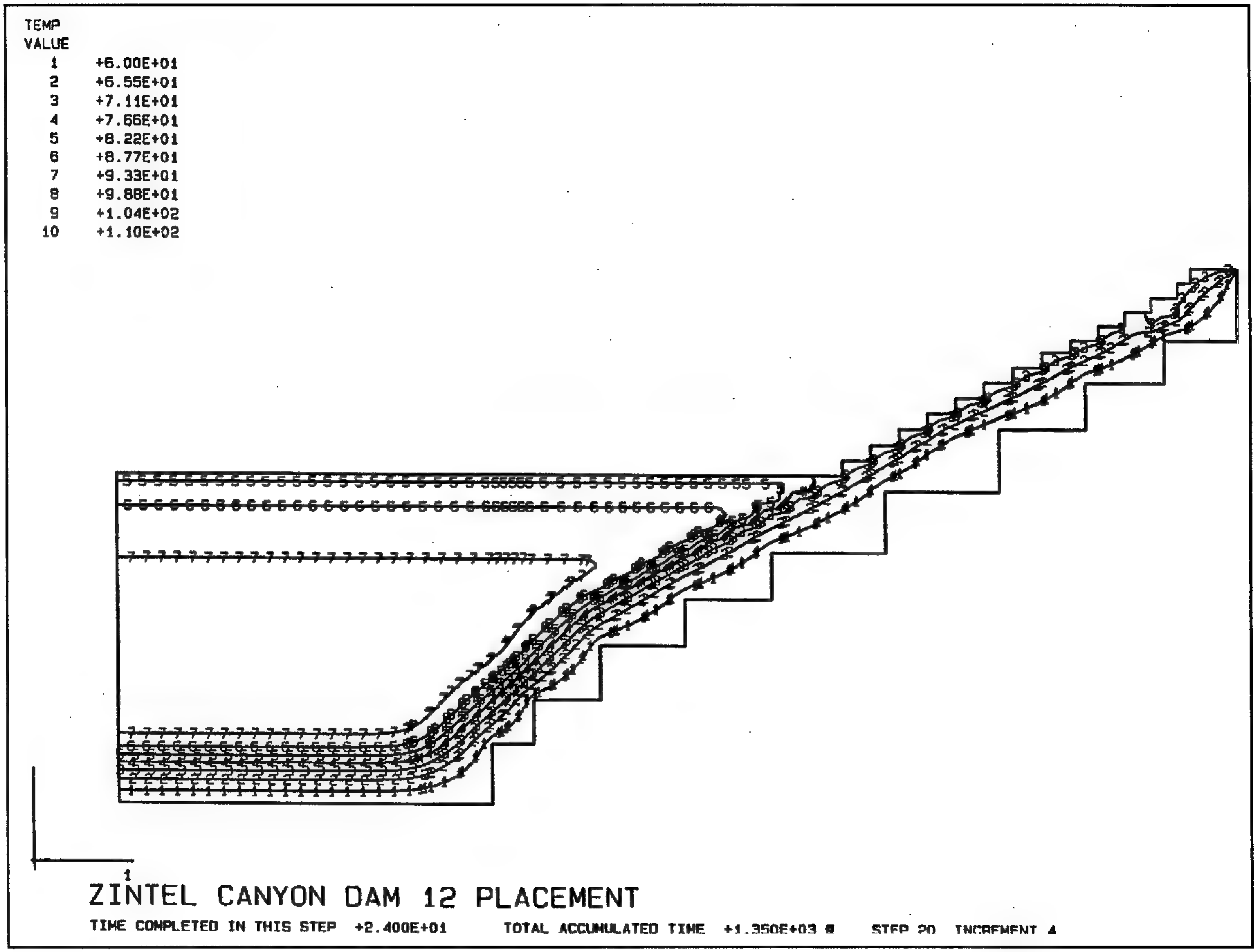


Figure 9. Temperature contours, longitudinal model, Zintel Canyon Dam 12 placement

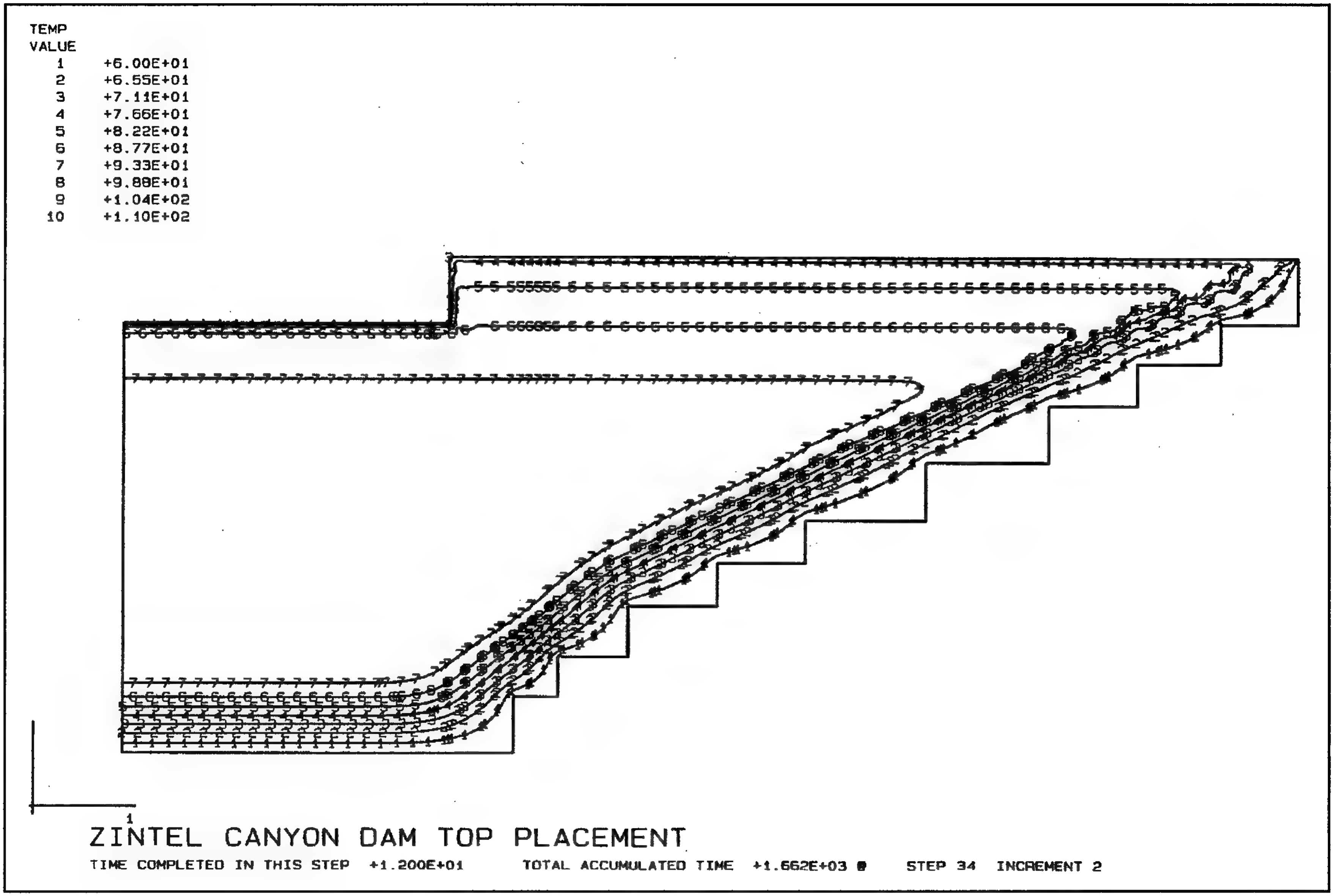


Figure 10. Temperature contours, longitudinal model, Zintel Canyon Dam-top placement

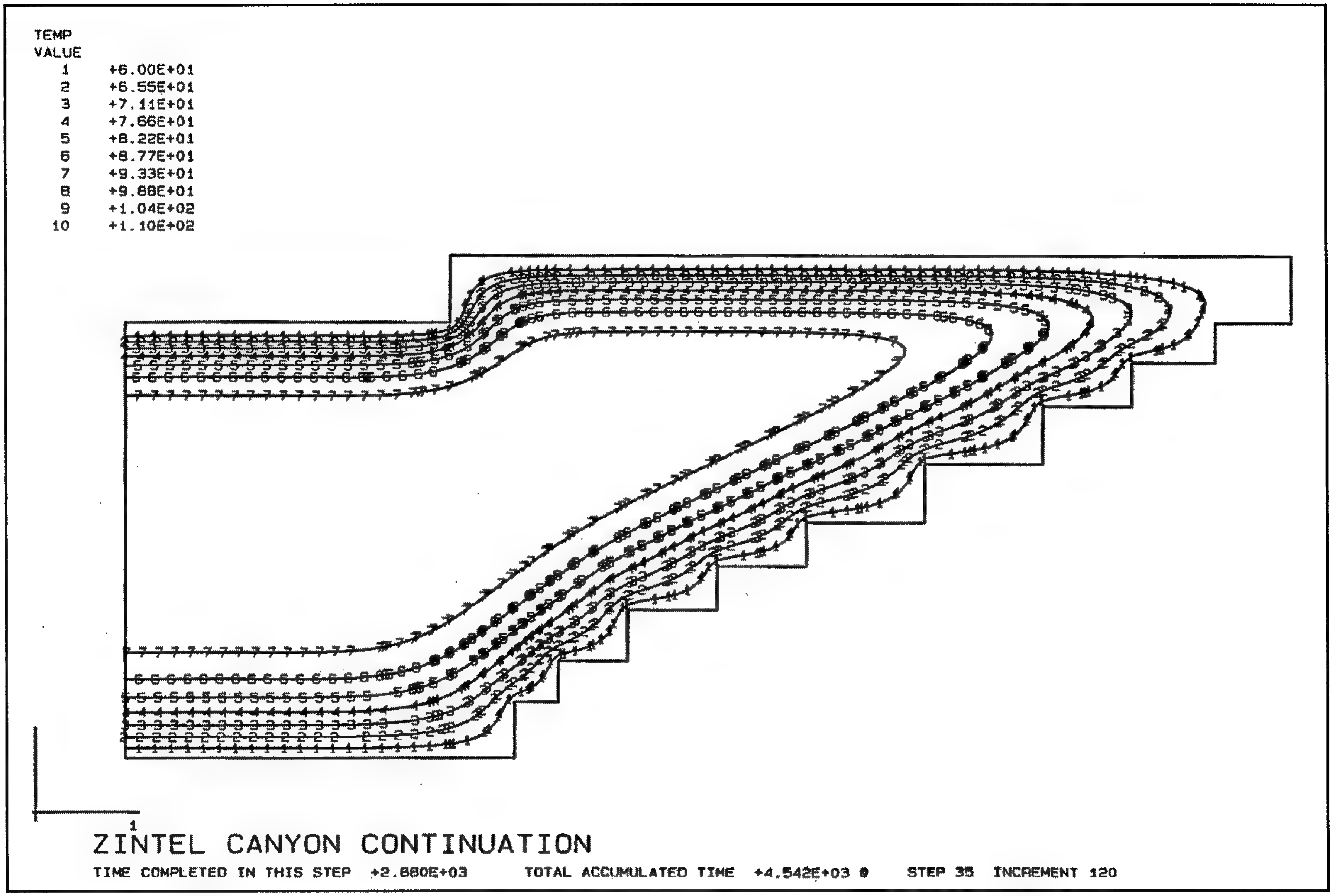
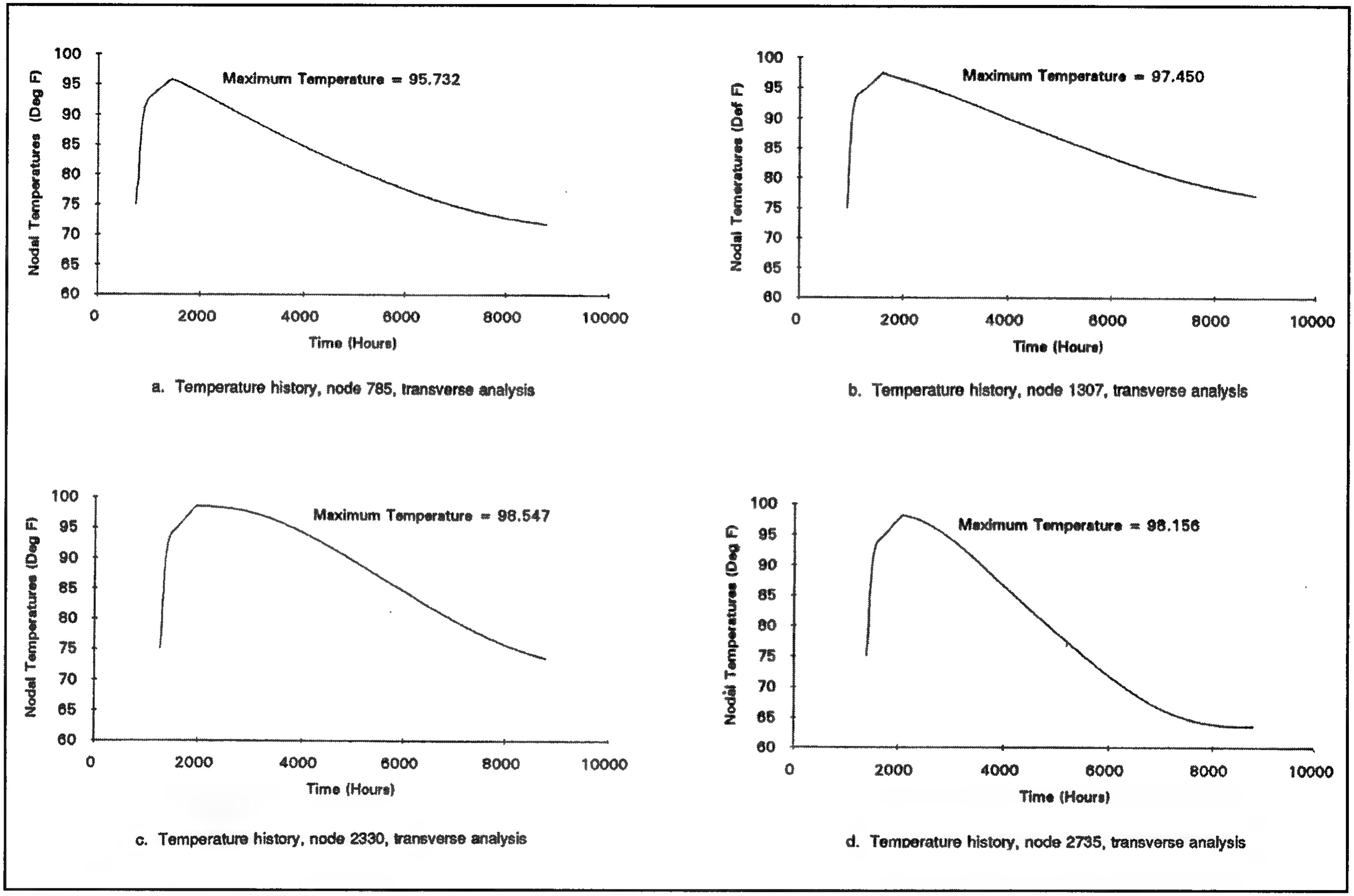


Figure 11. Temperature contours, longitudinal model, Zintel Canyon continuation



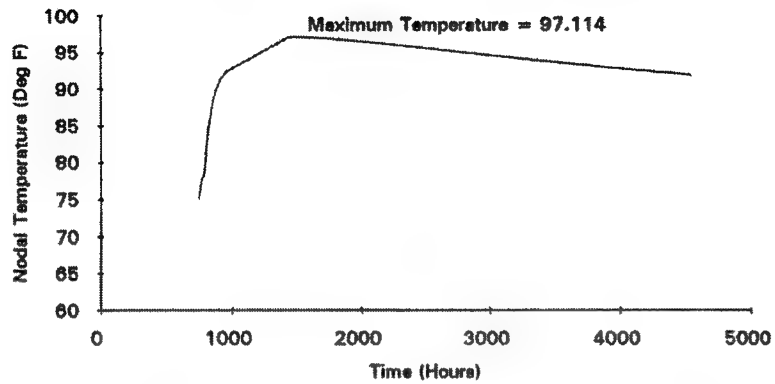
a. Temperature history, node 785, transverse analysis

b. Temperature history, node 1307, transverse analysis

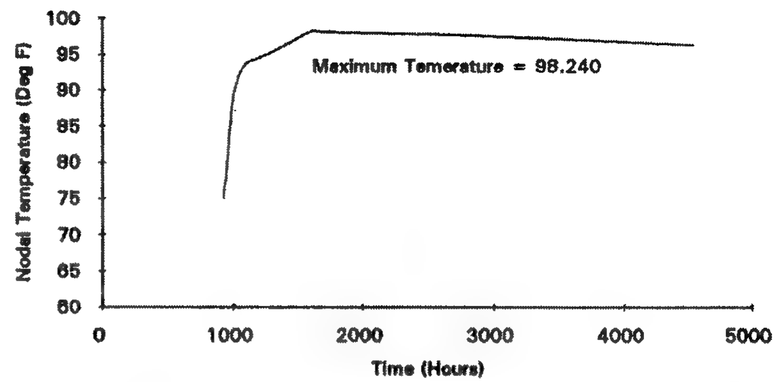
c. Temperature history, node 2330, transverse analysis

d. Temperature history, node 2735, transverse analysis

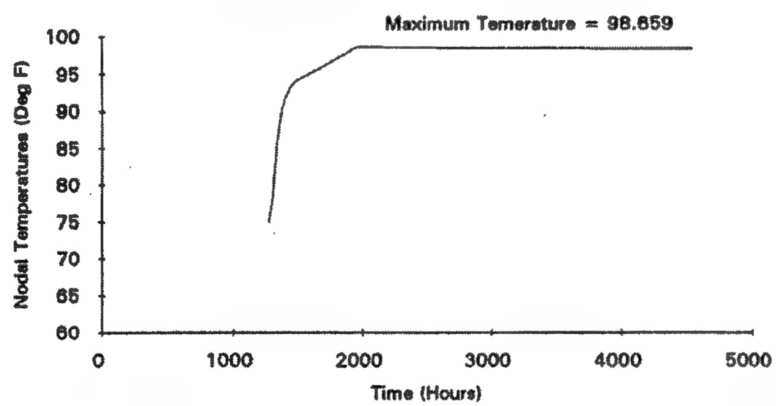
Figure 12. Transverse temperature histories



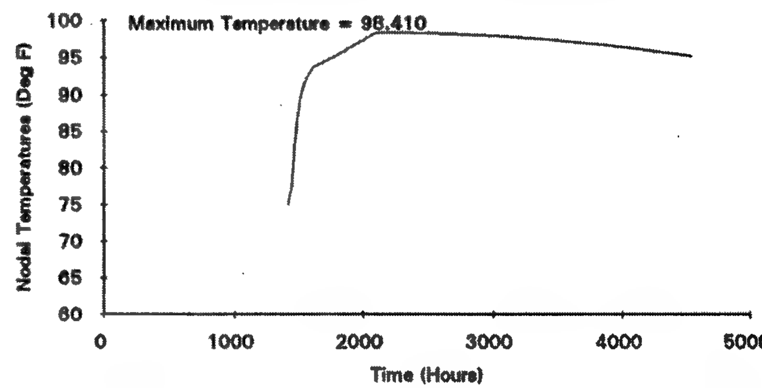
a. Temperature history, node 747, longitudinal analysis



b. Temperature history, node 1417, longitudinal analysis



c. Temperature history, node 3213, longitudinal analysis



d. Temperature history, node 4411, longitudinal analysis

Figure 13. Nodal temperature histories

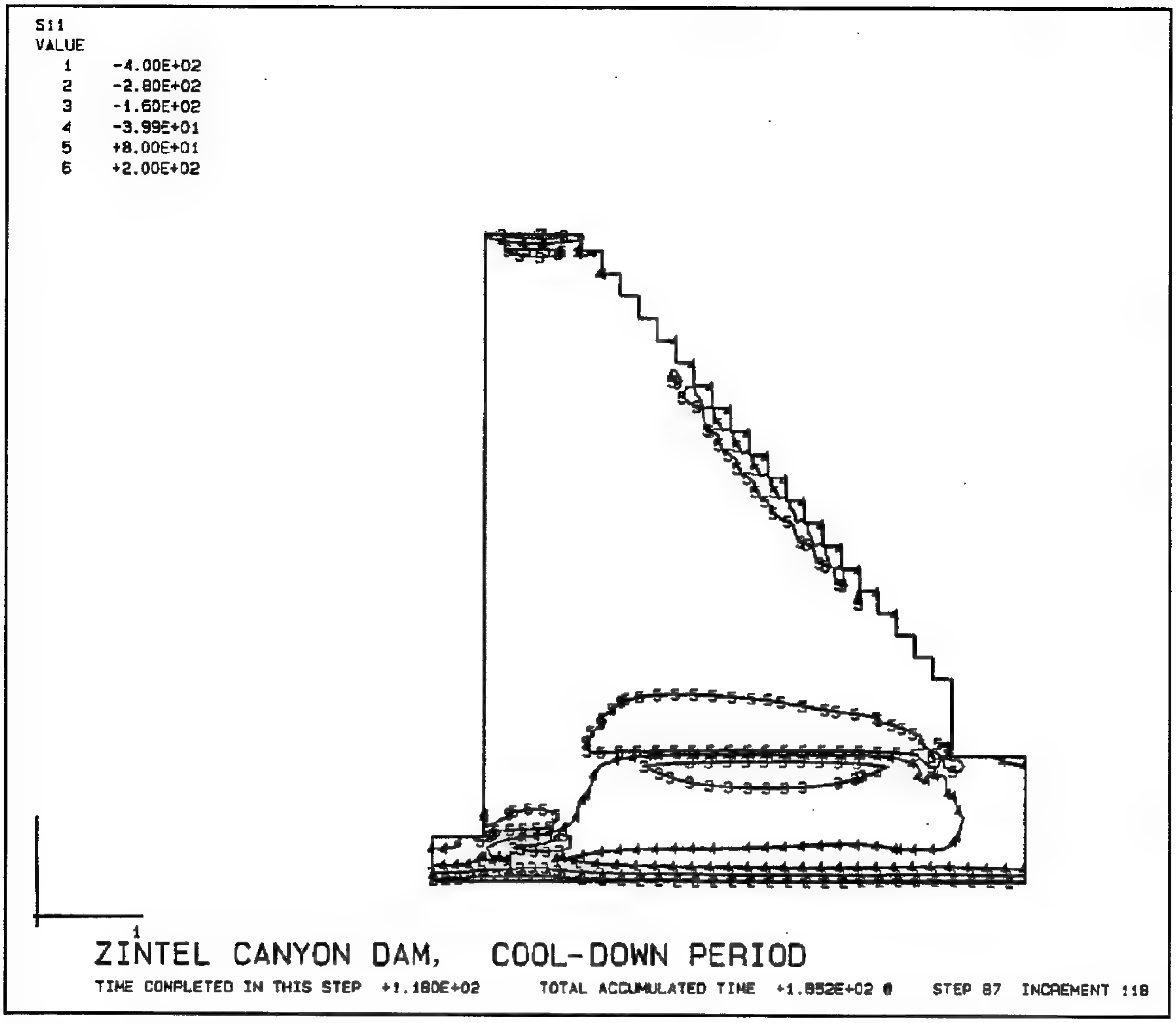


Figure 14. Global "X" stress contours, transverse model, Zintel Canyon Dam, cool-down period

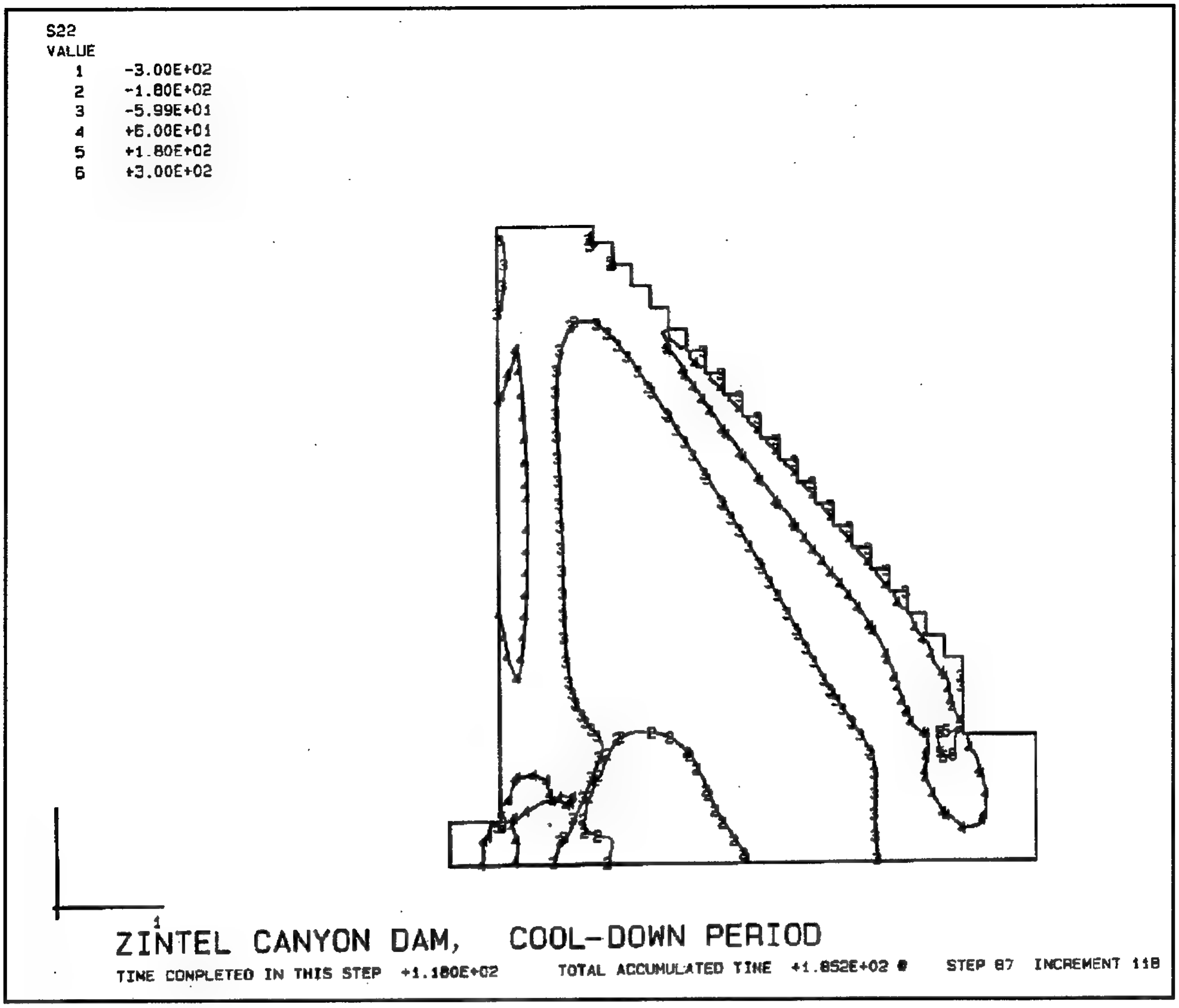


Figure 15. Global "Y" stress contours, transverse model, Zintel Canyon Dam, cool-down period

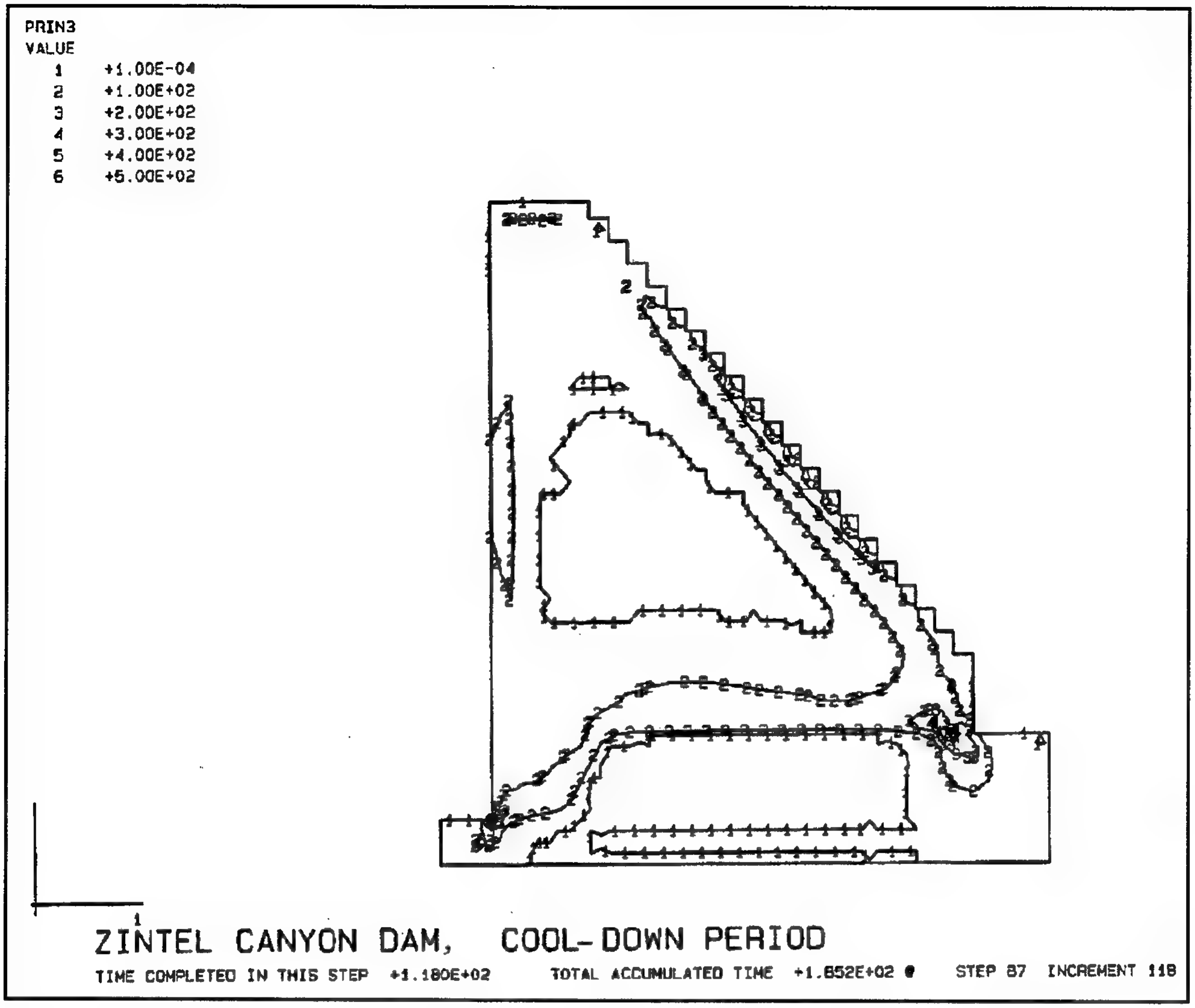


Figure 16. Principal stress contours, transverse model, Zintel Canyon Dam, cool-down period

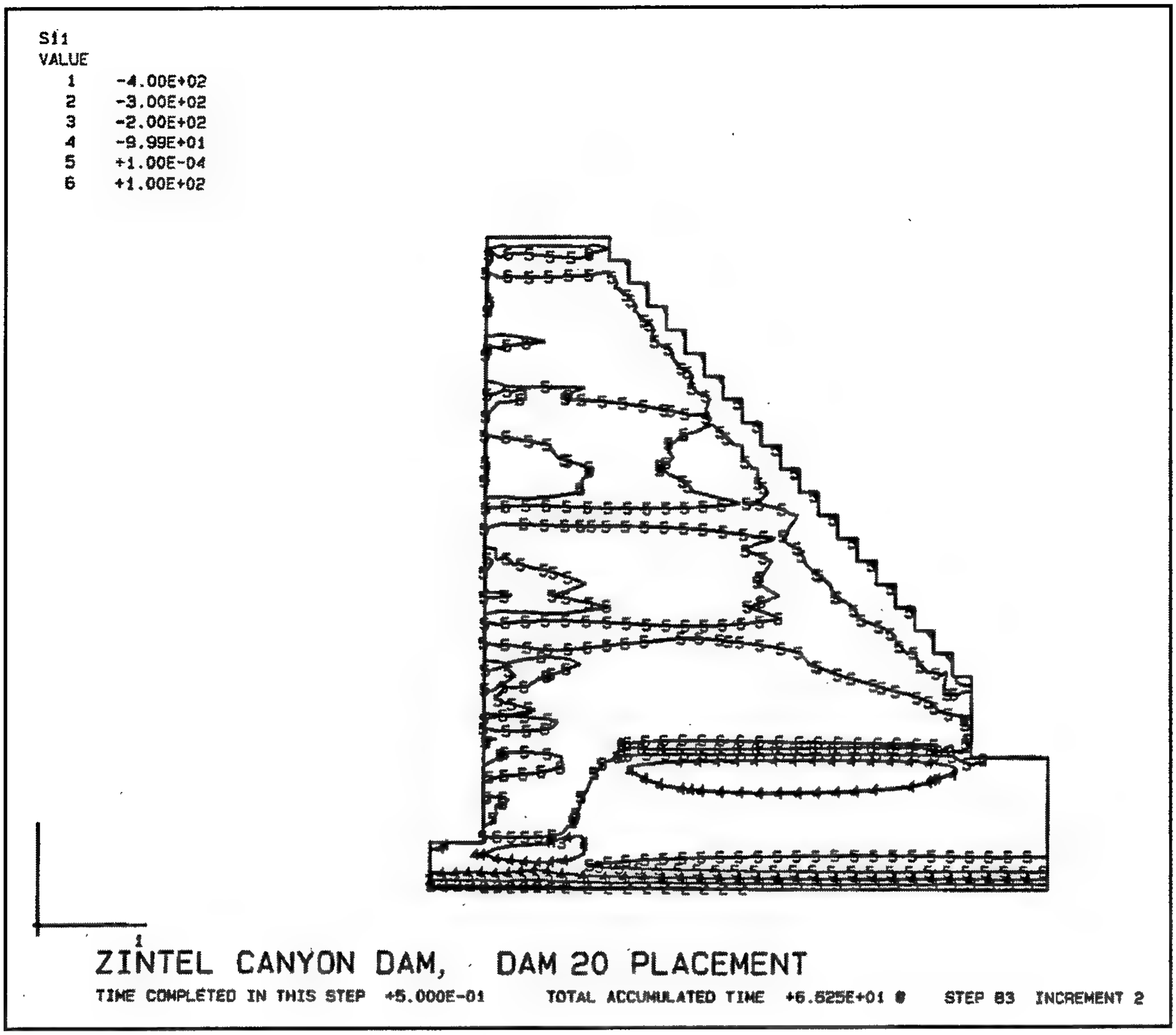


Figure 17. Global "X" stress contours, transverse model, Zintel Canyon Dam, Dam 20 placement

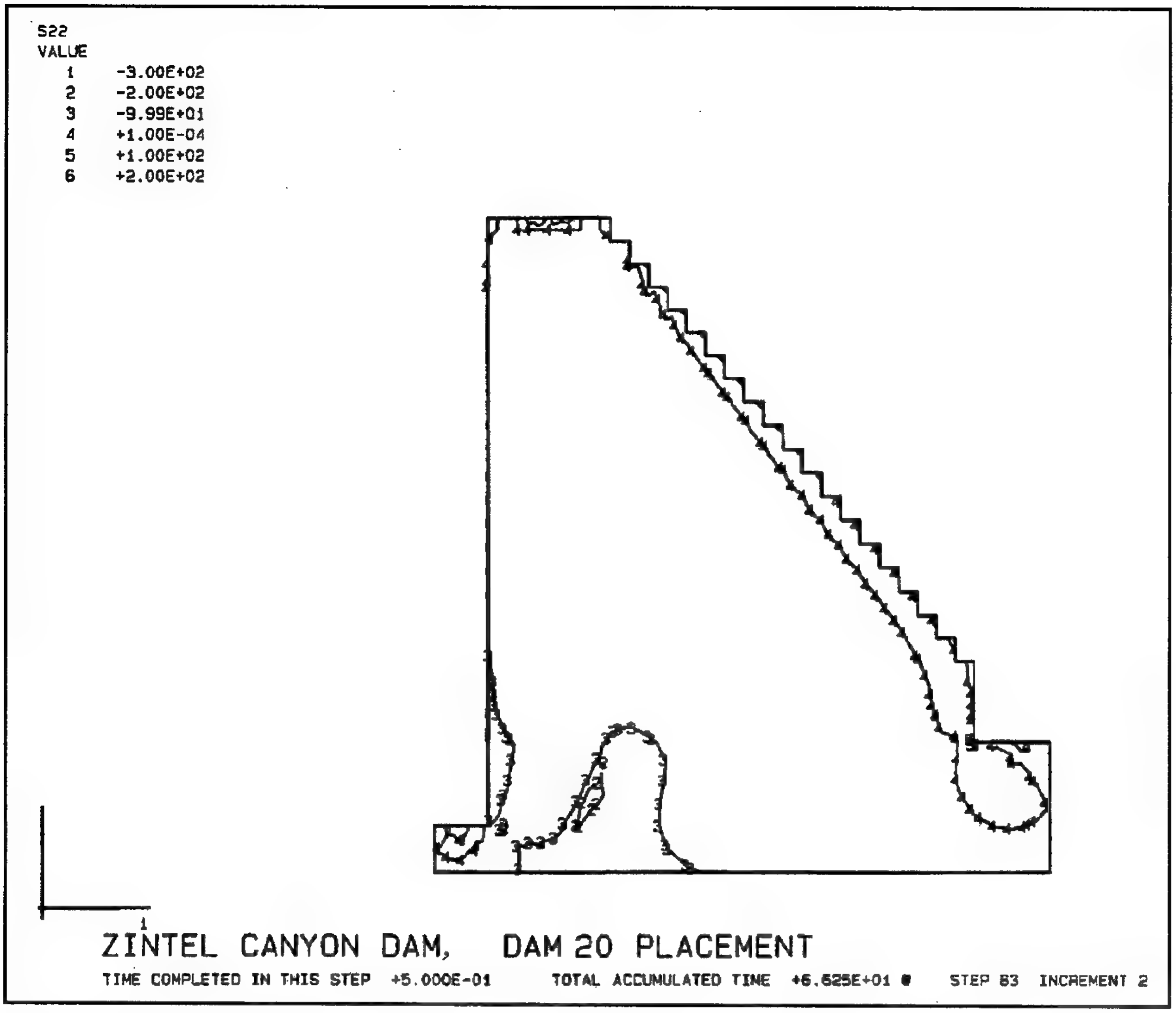


Figure 18. Global "Y" stress contours, transverse model, Zintel Canyon Dam, Dam 20 placement

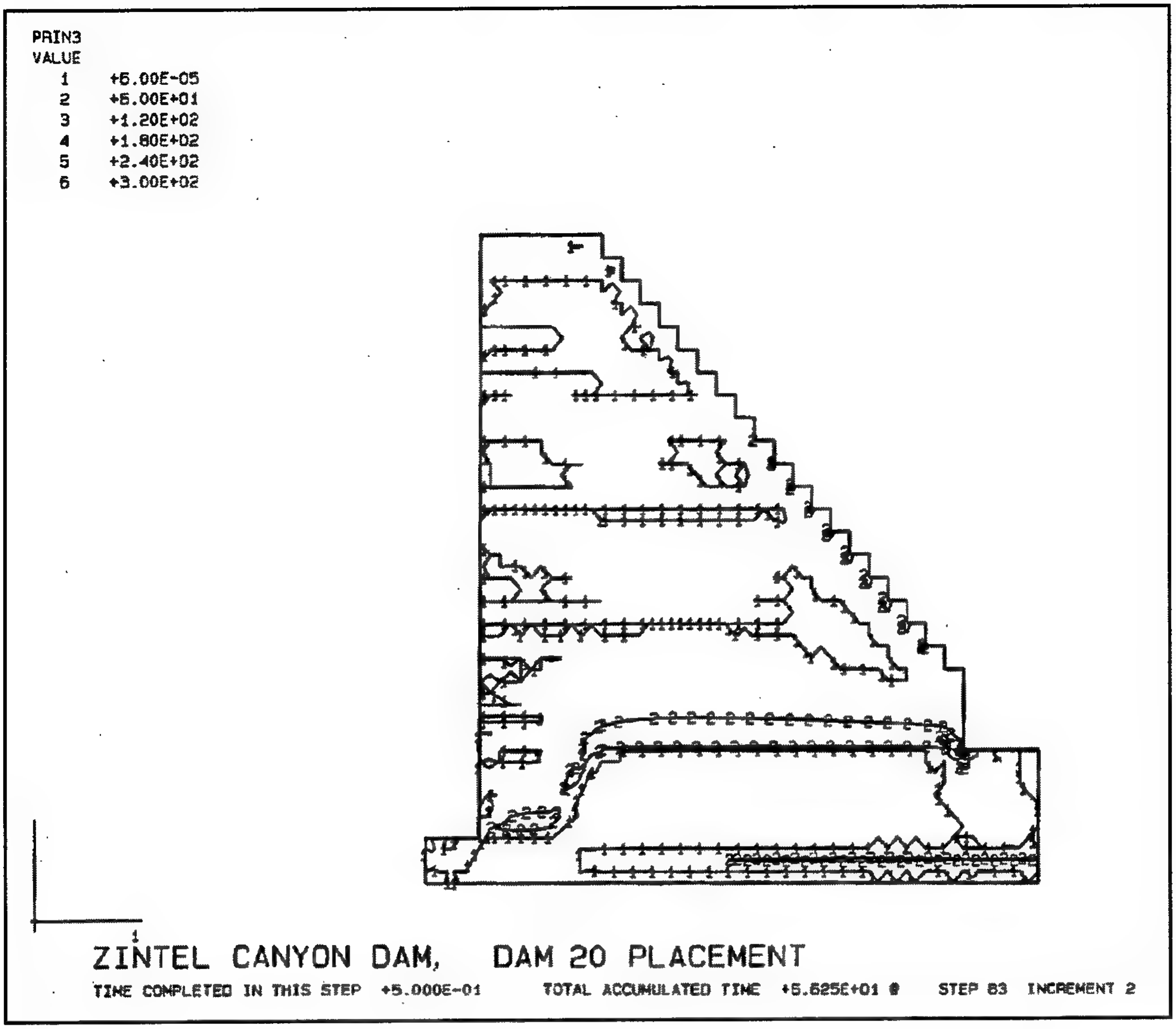


Figure 19. Principal stress contours, transverse model, Zintel Canyon Dam, Dam 20 placement

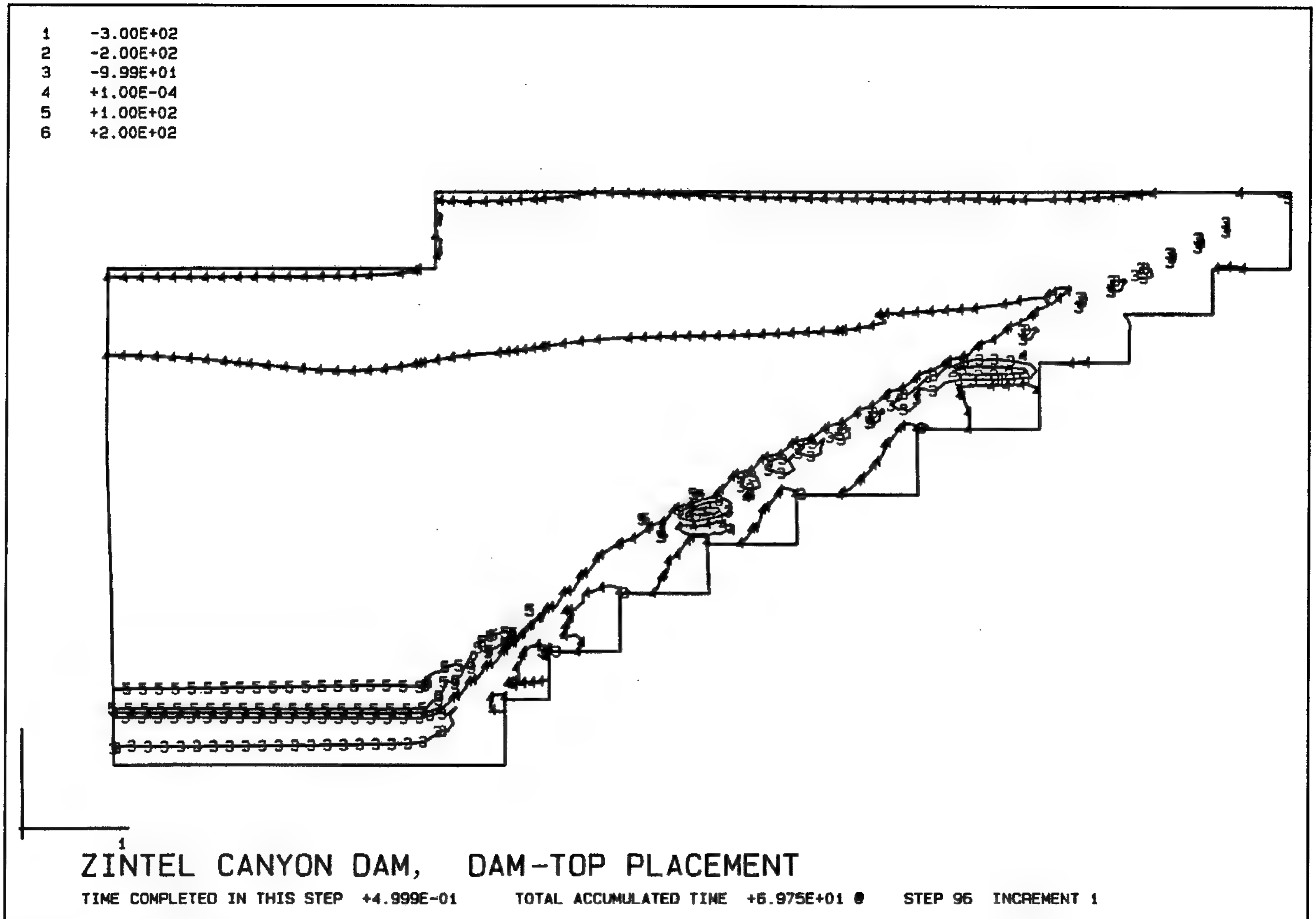


Figure 20. Global "X" stress contours longitudinal model, Zintel Canyon Dam, dam-top placement

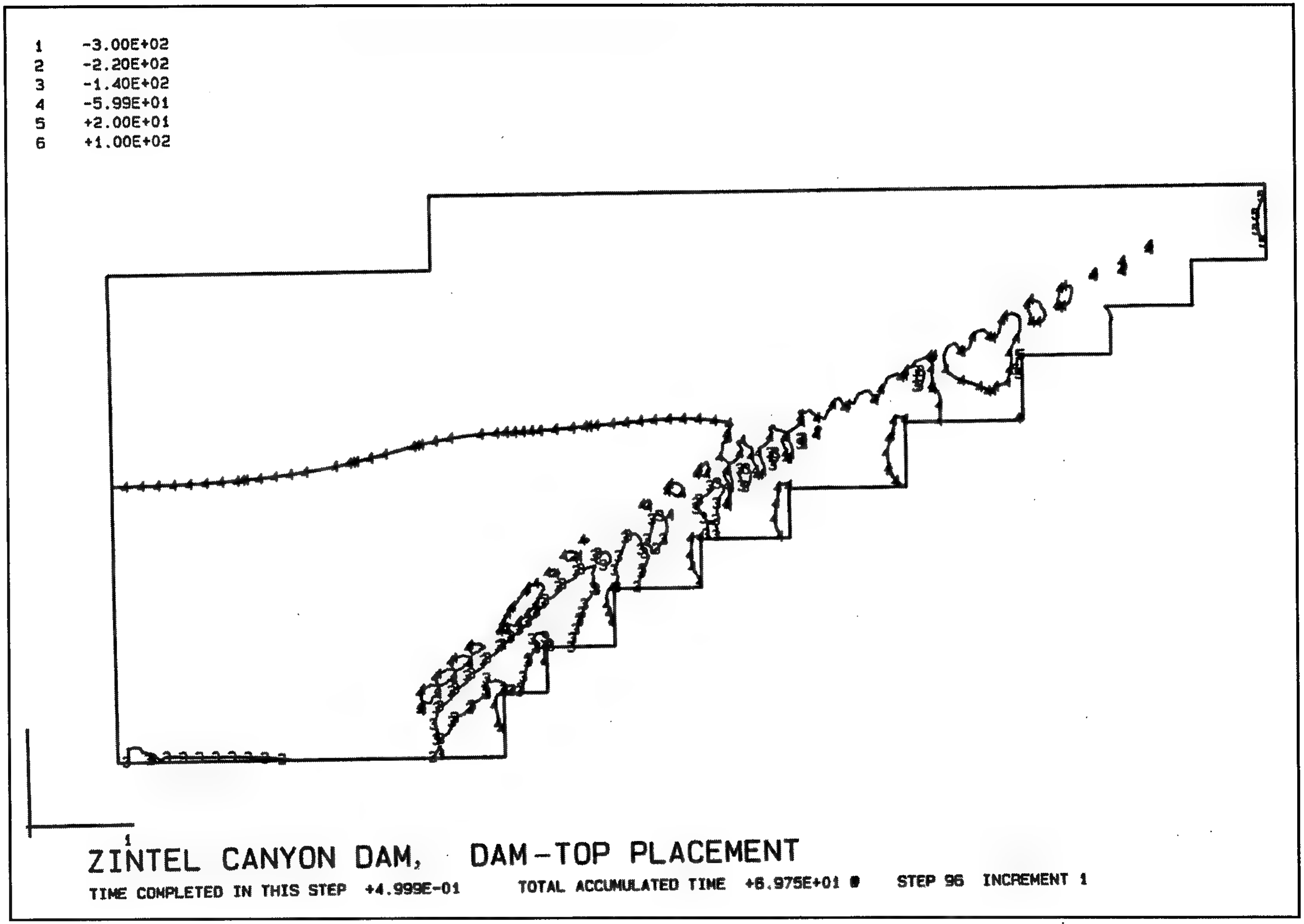


Figure 21. Global "Y" stress contour, longitudinal model, Zintel Canyon Dam, dam-top placement

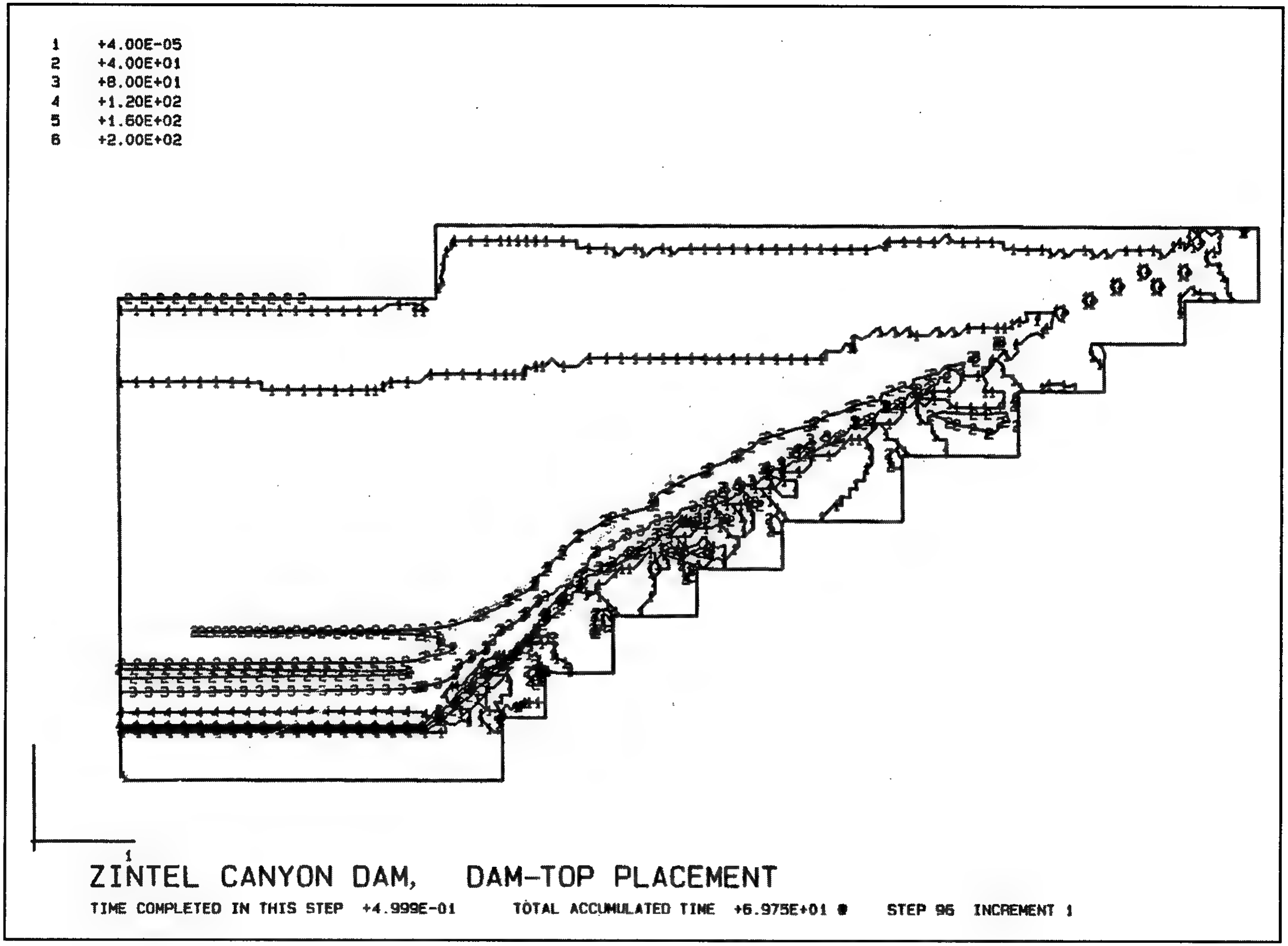


Figure 22. Principal stress contours, longitudinal model, Zintel Canyon Dam, dam-top placement

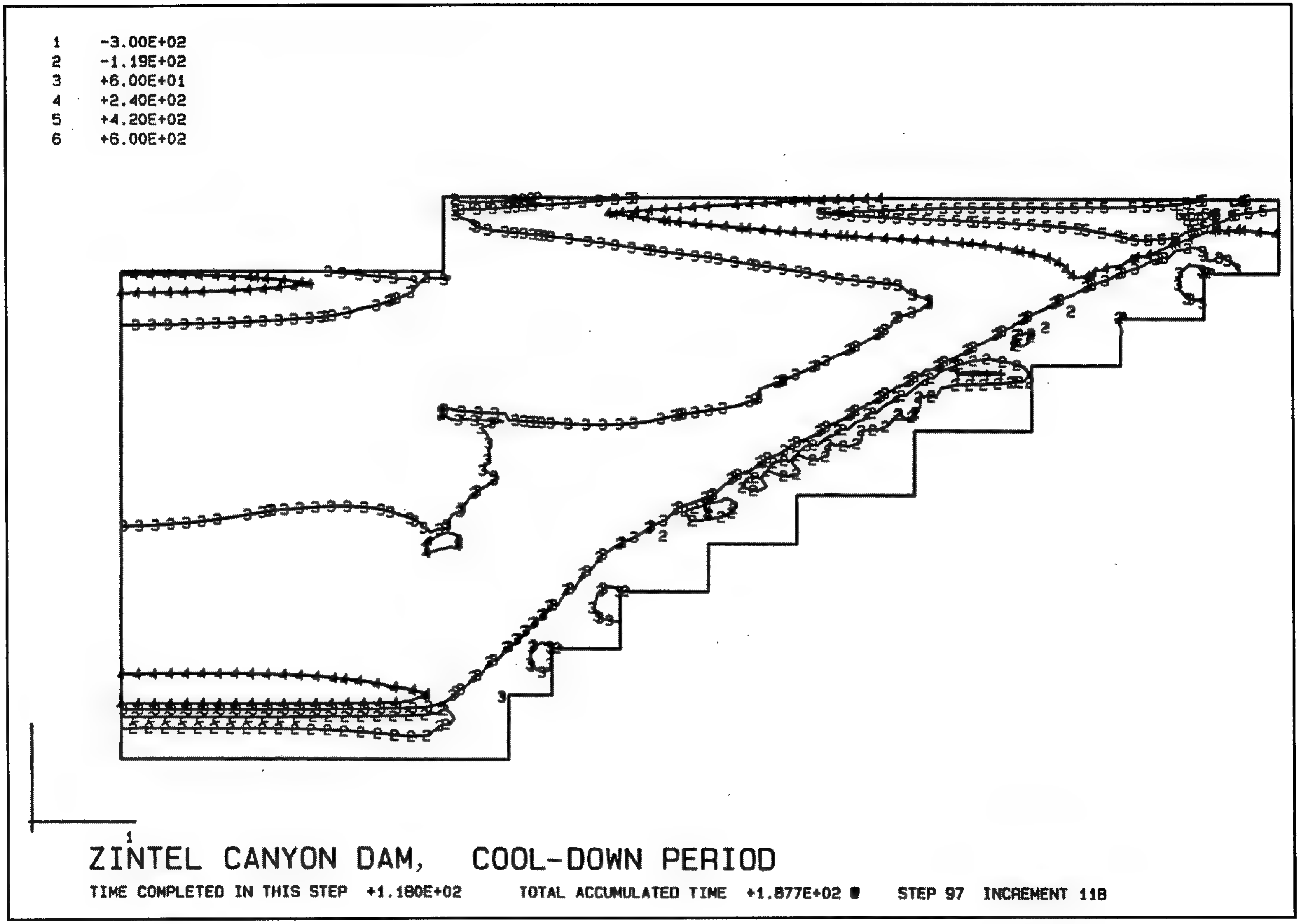


Figure 23. Global "X" stress contours, longitudinal model, Zintel Canyon Dam, cool-down period

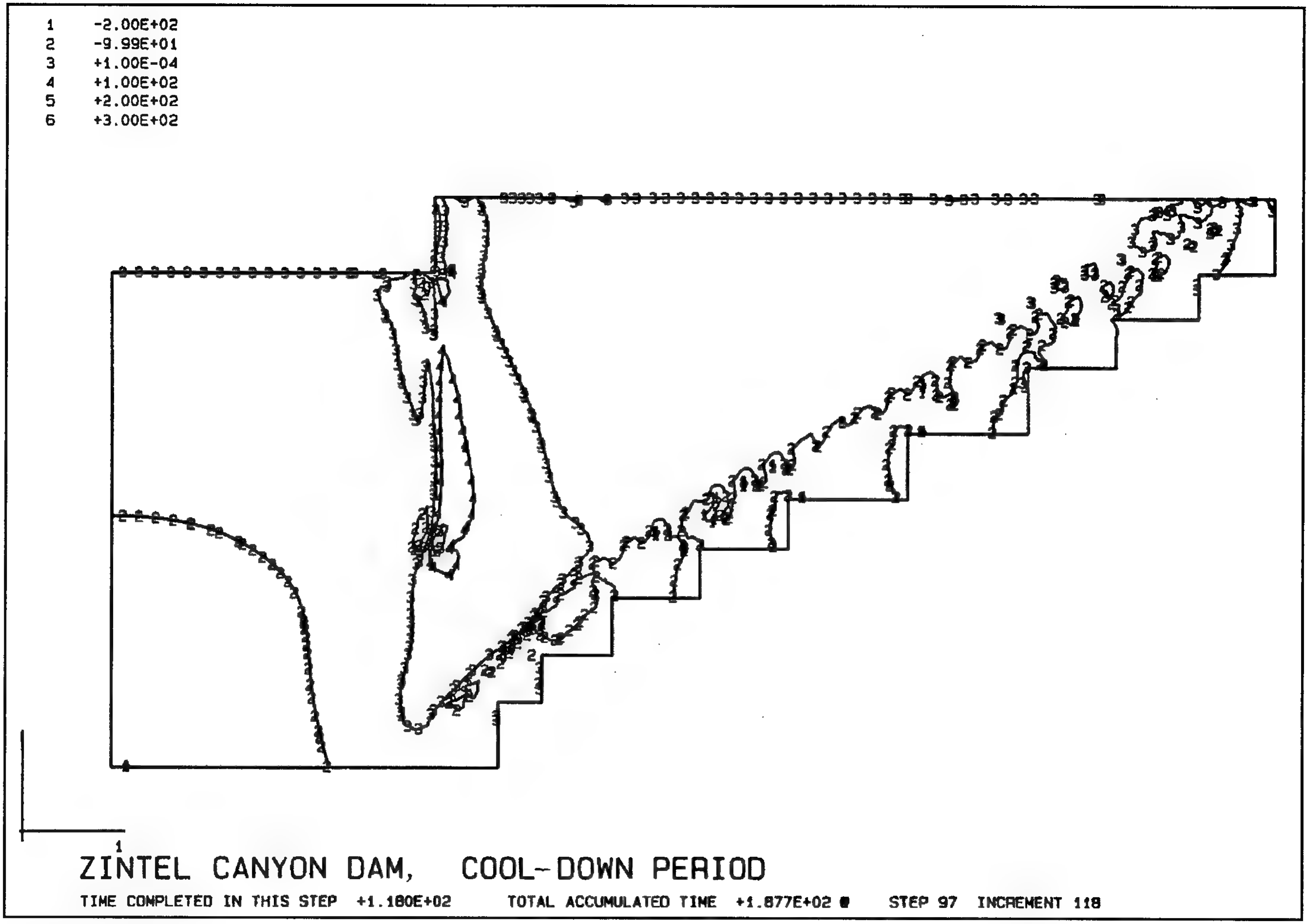


Figure 24. Global "Y" stress contours, longitudinal model, Zintel Canyon Dam, cool-down period

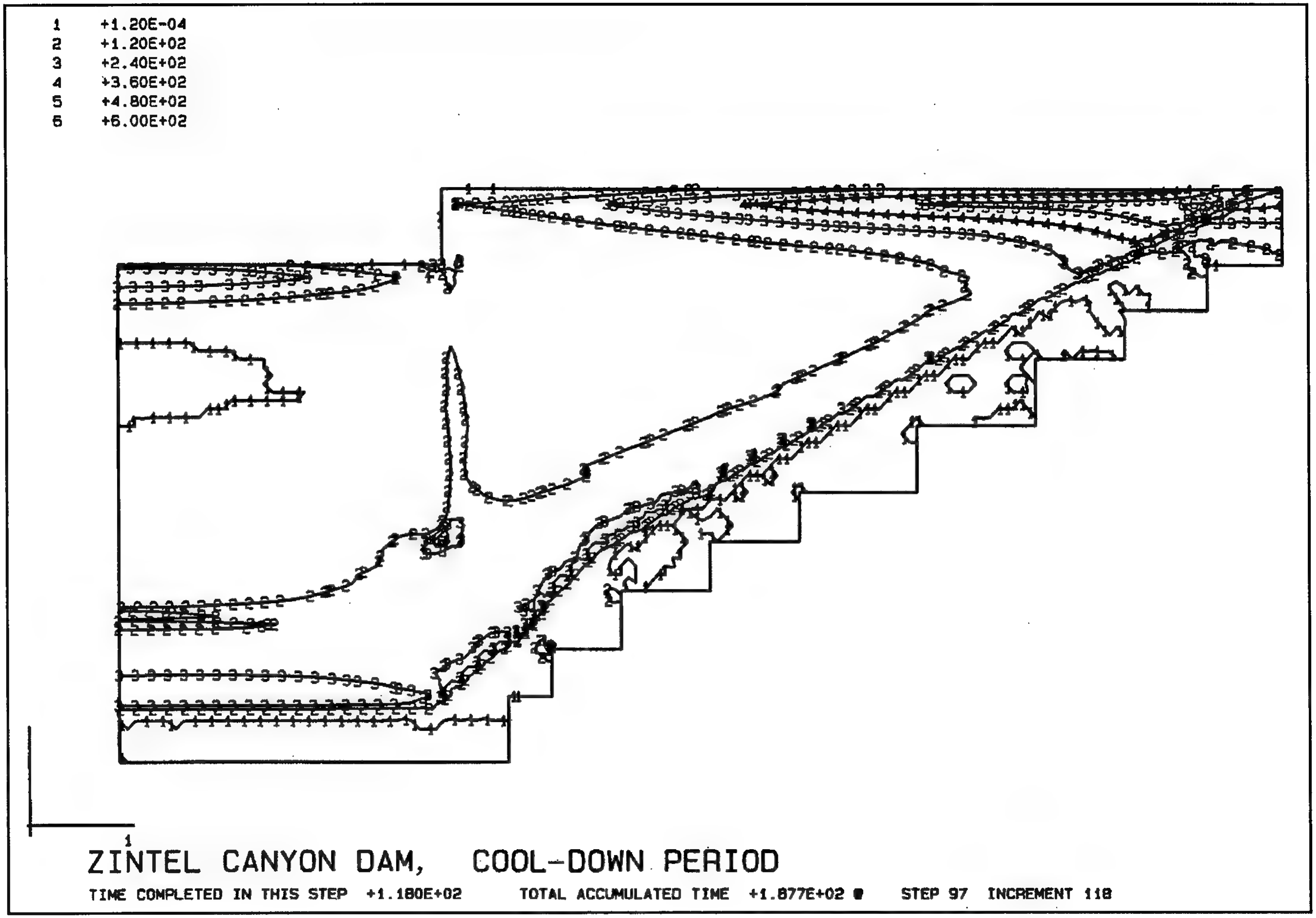
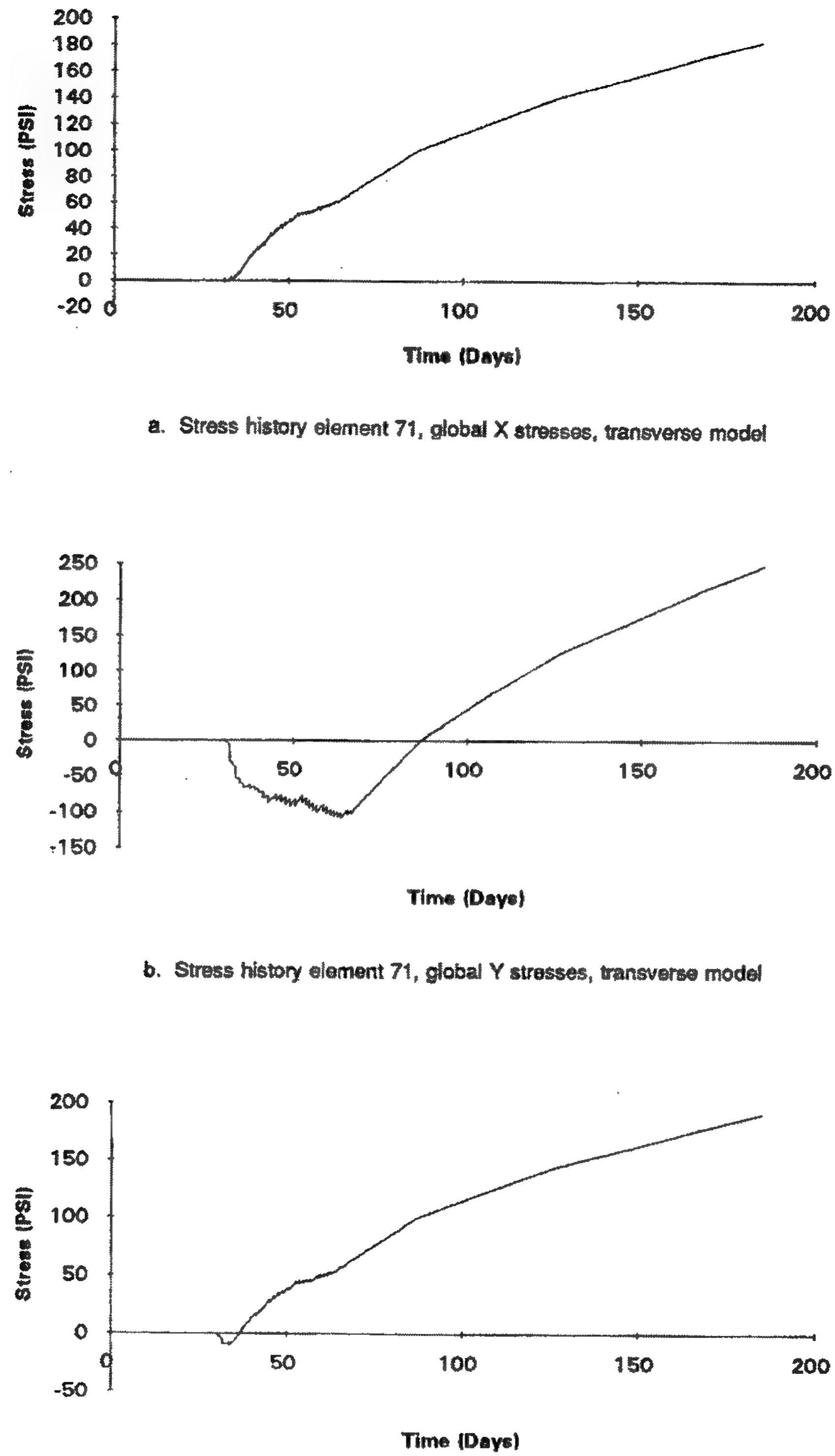


Figure 25. Principal stress contours, longitudinal model, Zintel Canyon Dam, cool-down period

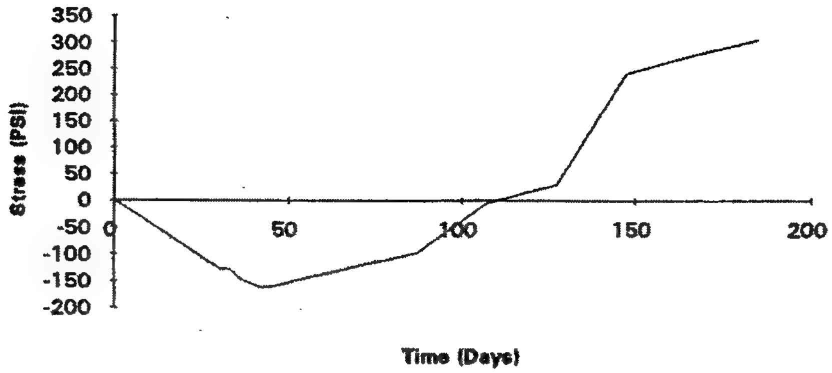


a. Stress history element 71, global X stresses, transverse model

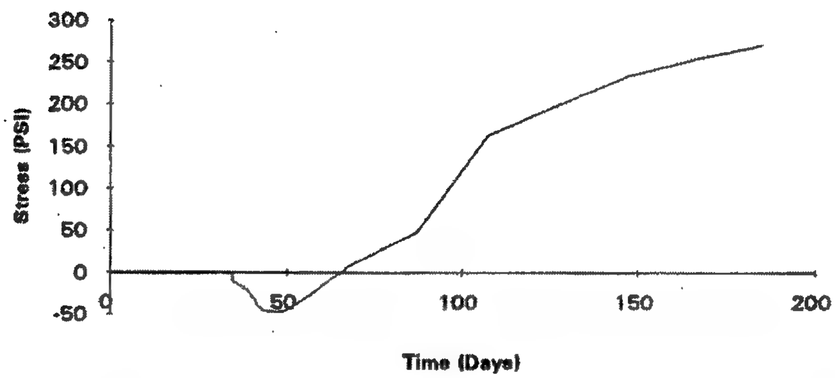
b. Stress history element 71, global Y stresses, transverse model

c. Stress history element 71, shear stresses, transverse analysis

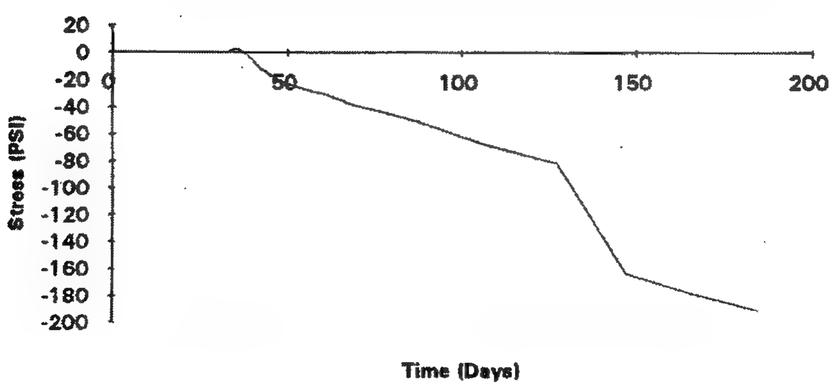
Figure 26. Stress histories for elements, transverse model, element 71



a. Stress history element 188, global X stresses, transverse model

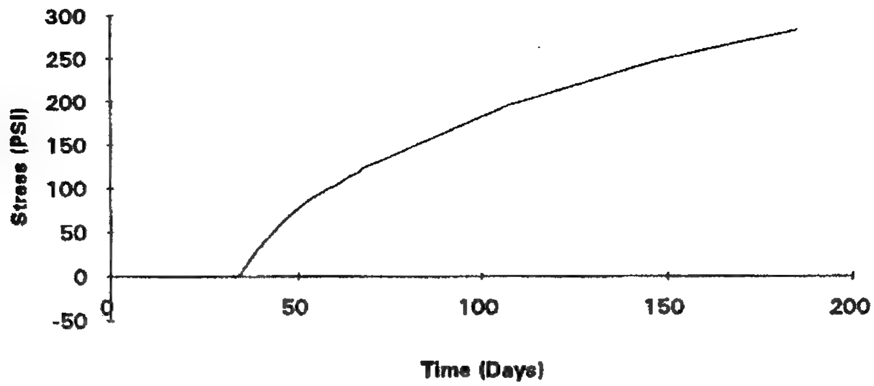


b. Stress history element 188, global Y stresses, transverse model

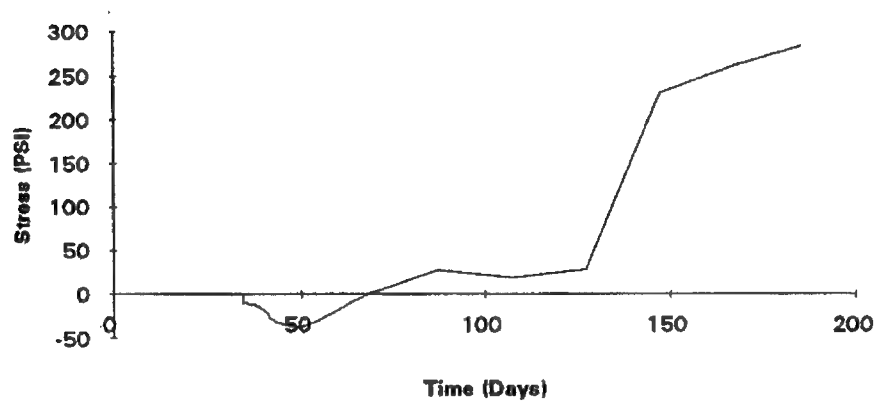


c. Stress history element 188, shear stresses, transverse model

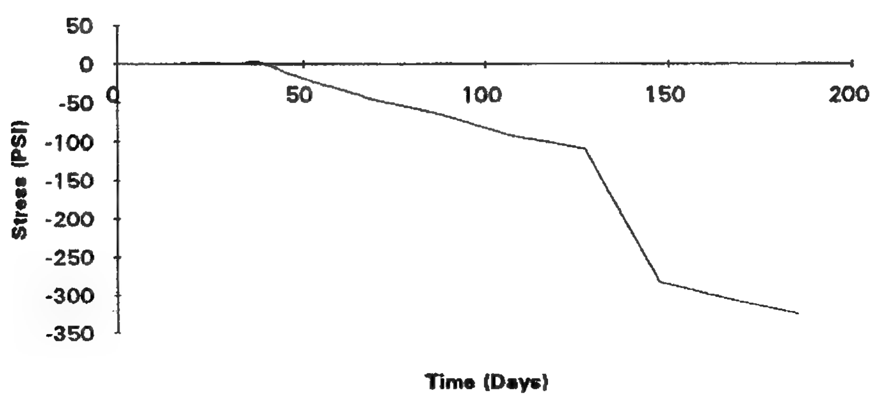
Figure 27. Stress histories for elements, transverse model, element 188



a. Stress history element 216, global X stresses, transverse model

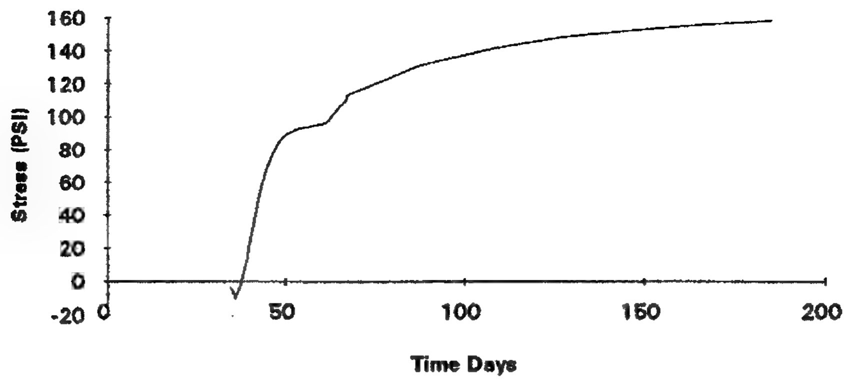


b. Stress history element 216, global Y stresses, transverse model

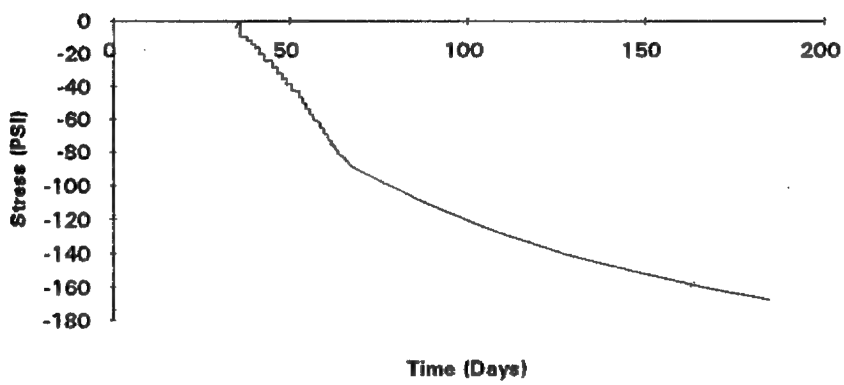


c. Stress history element 216, shear stresses, transverse model

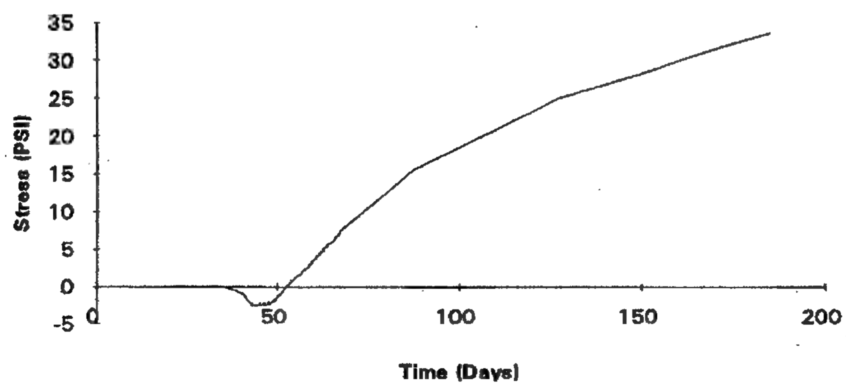
Figure 28. Stress histories for elements, transverse model, element 216



a. Stress history element 227, global X stresses, transverse model

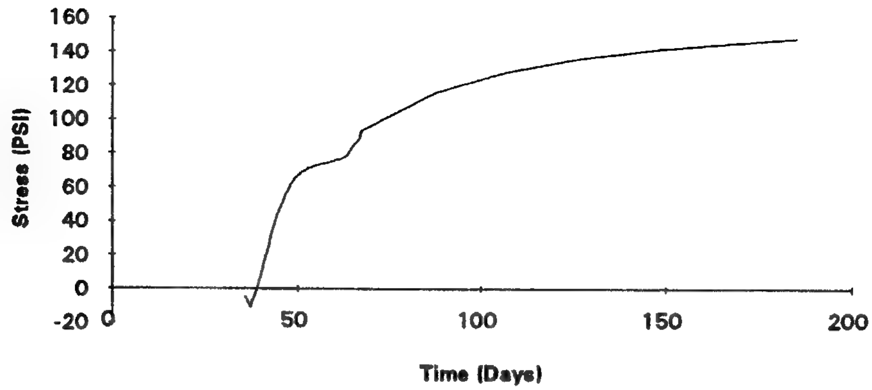


b. Stress history element 227, global Y stresses, transverse model

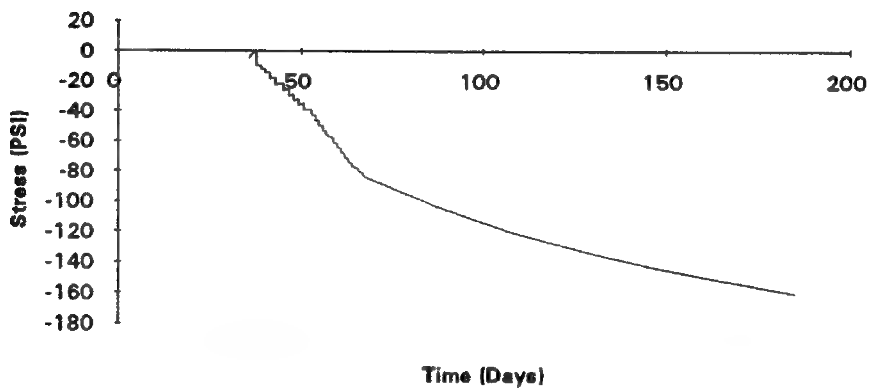


c. Stress history element 227, shear stresses, transverse model

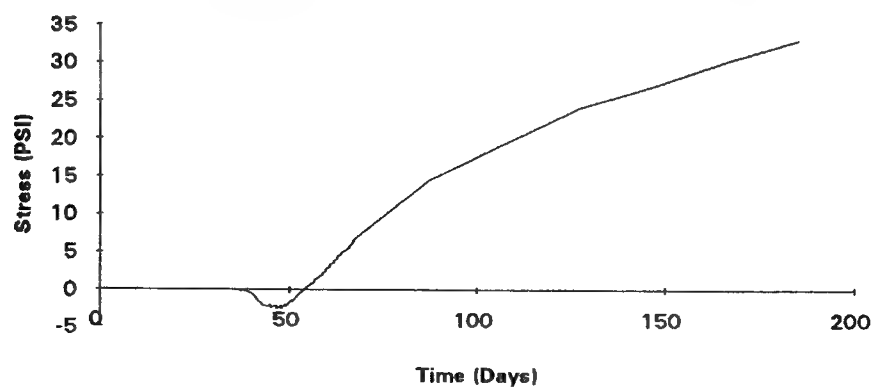
Figure 29. Stress histories for elements, transverse model, element 227



a. Stress history element 252, global X stresses, transverse model

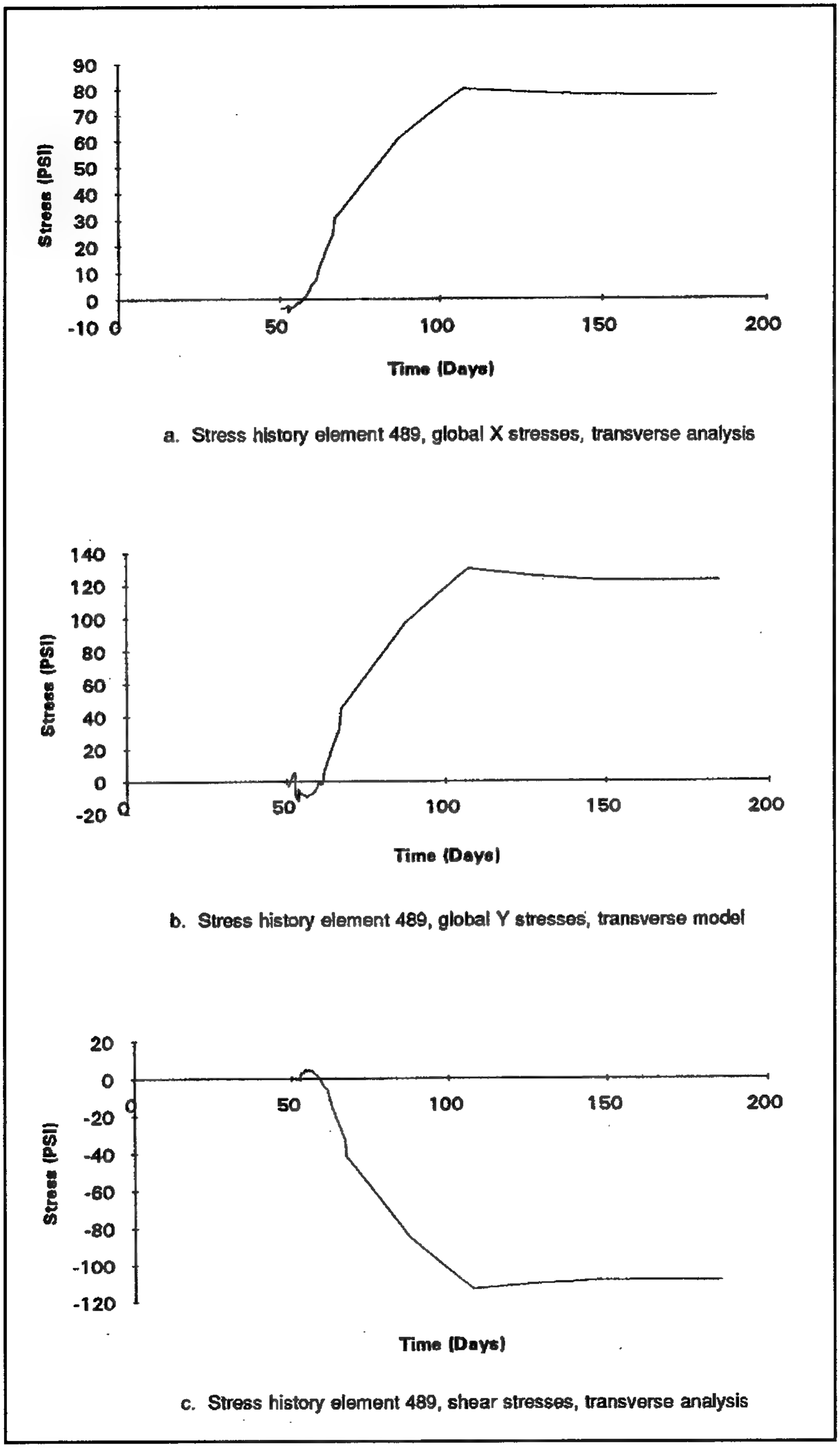


b. Stress history element 252, global Y stresses, transverse model



c. Stress history element 252, shear stresses, transverse analysis

Figure 30. Stress histories for elements, transverse model, element 252

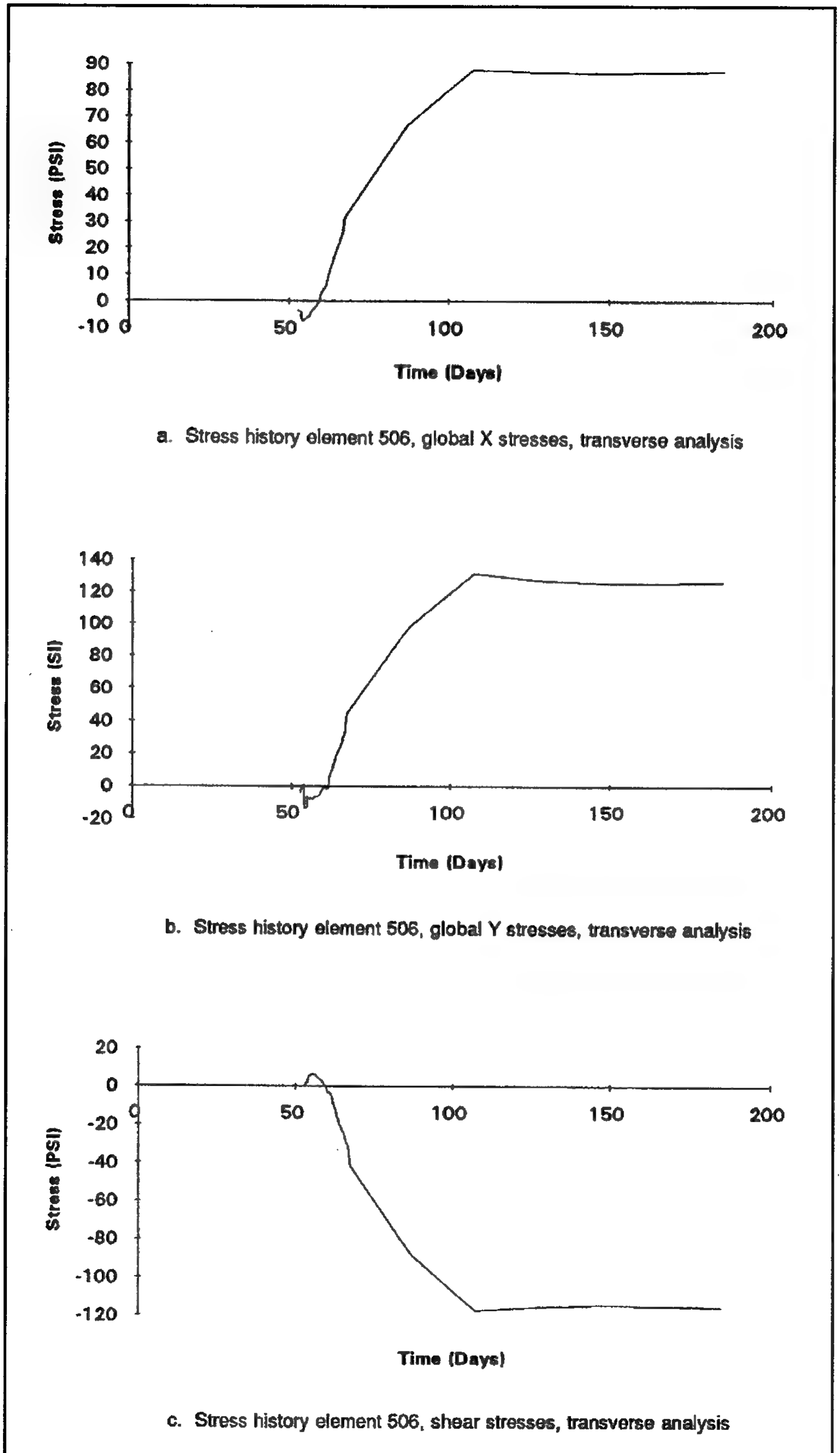


a. Stress history element 489, global X stresses, transverse analysis

b. Stress history element 489, global Y stresses, transverse model

c. Stress history element 489, shear stresses, transverse analysis

Figure 31. Stress histories for elements, transverse model, element 489

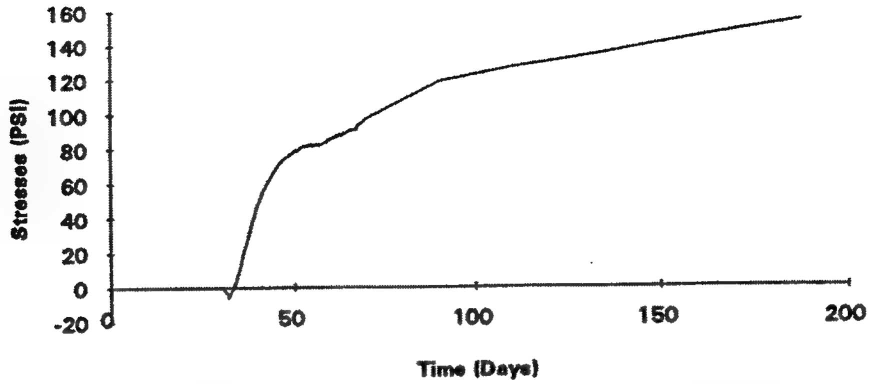


a. Stress history element 506, global X stresses, transverse analysis

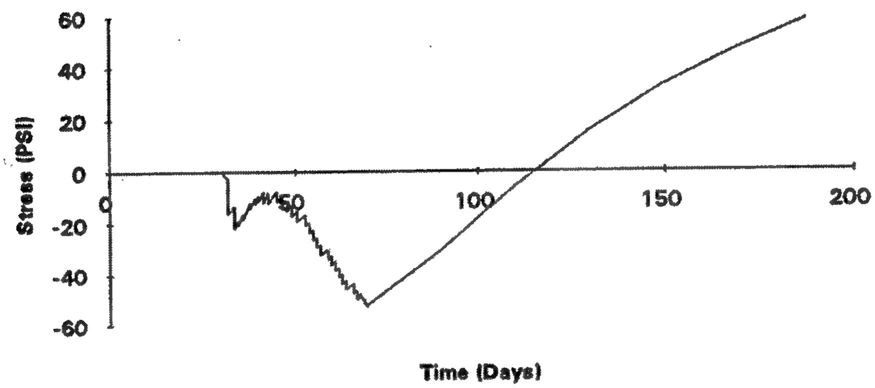
b. Stress history element 506, global Y stresses, transverse analysis

c. Stress history element 506, shear stresses, transverse analysis

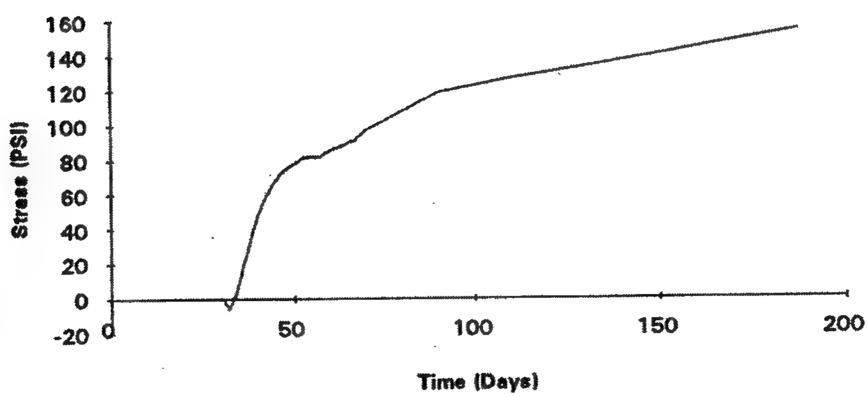
Figure 32. Stress histories for elements, transverse model, element 506



a. Stress history element 92, global X stresses, longitudinal model

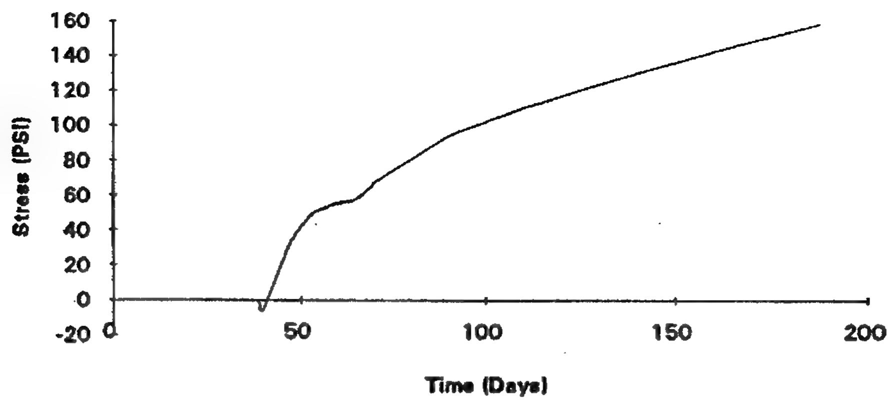


b. Stress history element 92, global Y stresses, longitudinal model

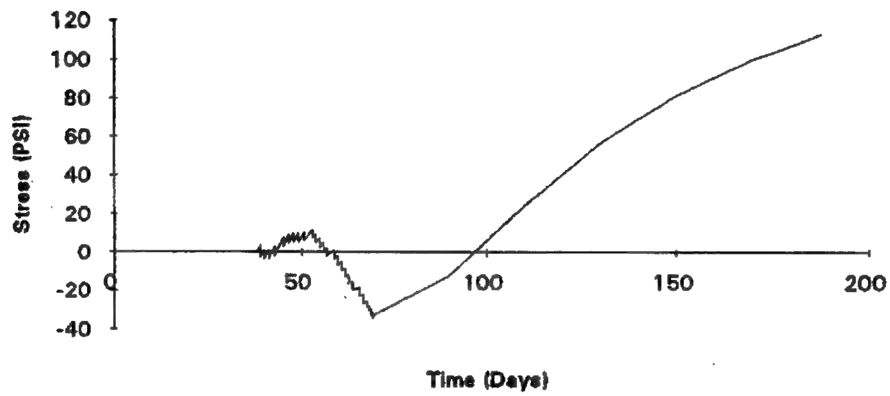


c. Stress history element 92, shear stresses, longitudinal model

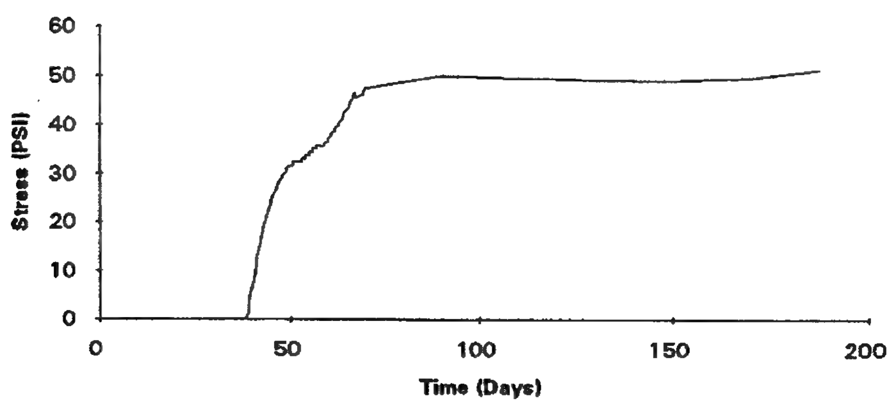
Figure 33. Stress histories for elements, longitudinal model, element 92



a. Stress history element 309, global X stresses, longitudinal model

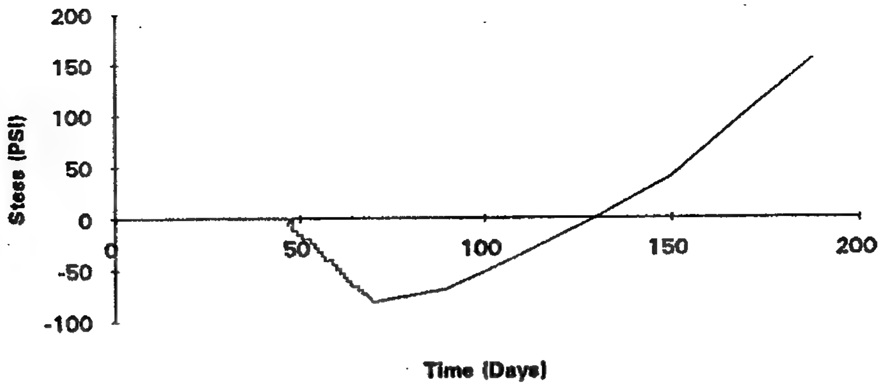


b. Stress history element 309, global Y stresses, longitudinal model

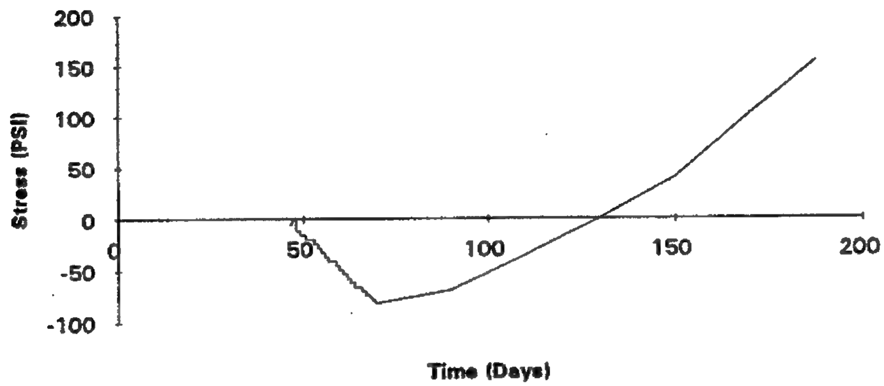


c. Stress history element 309, shear stresses, longitudinal model

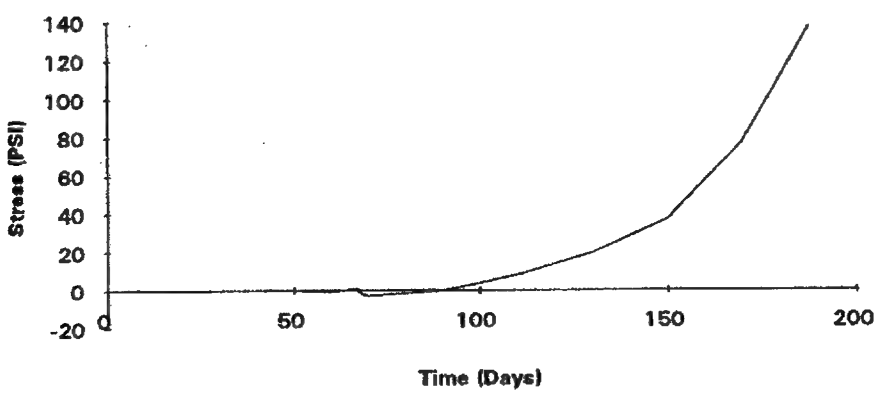
Figure 34. Stress histories for elements, longitudinal model, element 309



a. Stress history element 518, global X stresses, longitudinal model

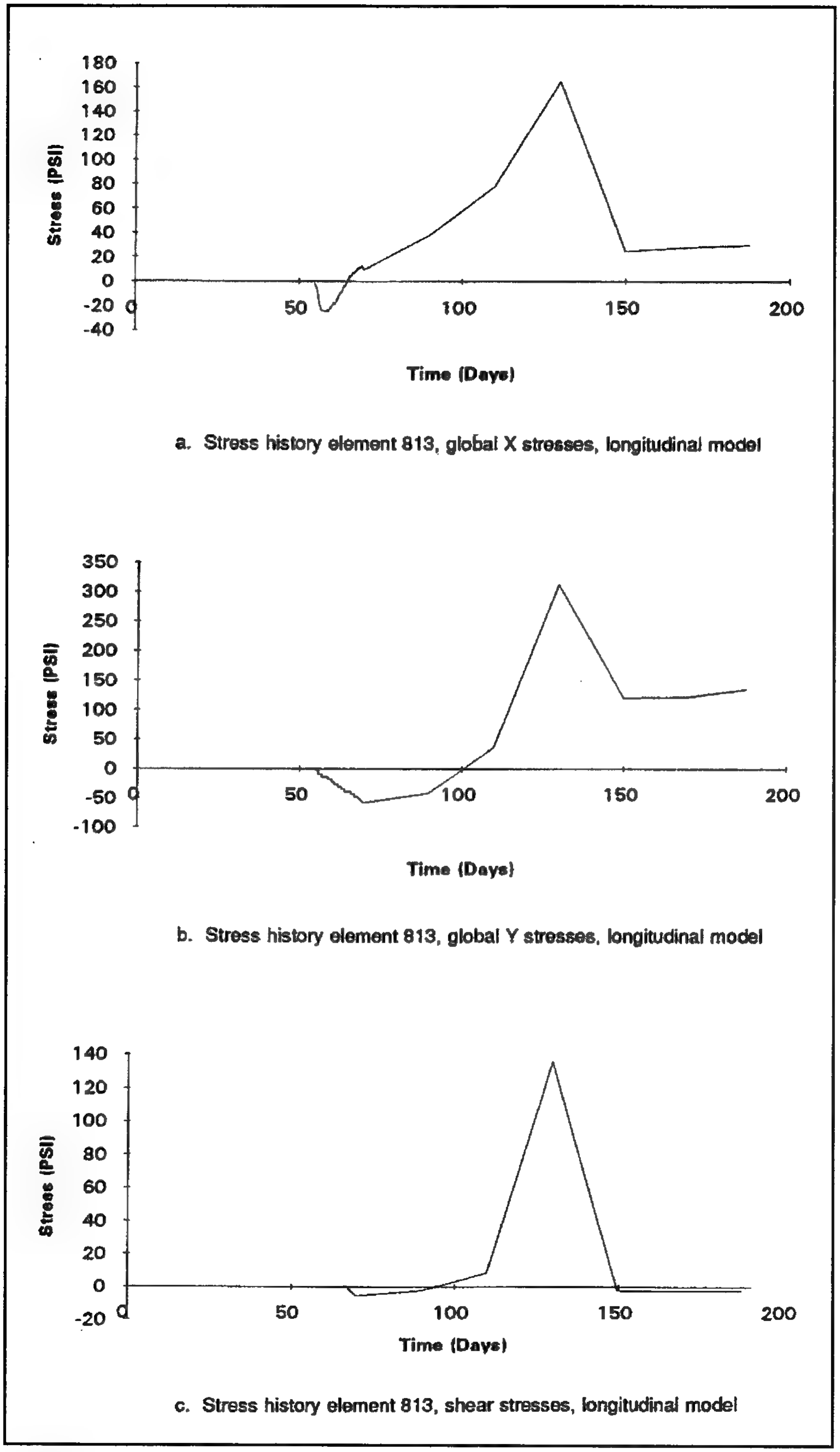


b. Stress history element 518, global Y stresses, longitudinal model



c. Stress history element 518, shear stresses, longitudinal model

Figure 35. Stress histories for elements, longitudinal model, element 518

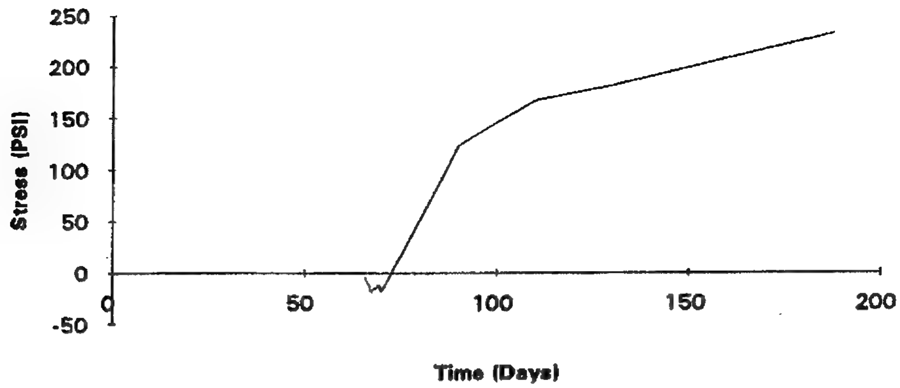


a. Stress history element 813, global X stresses, longitudinal model

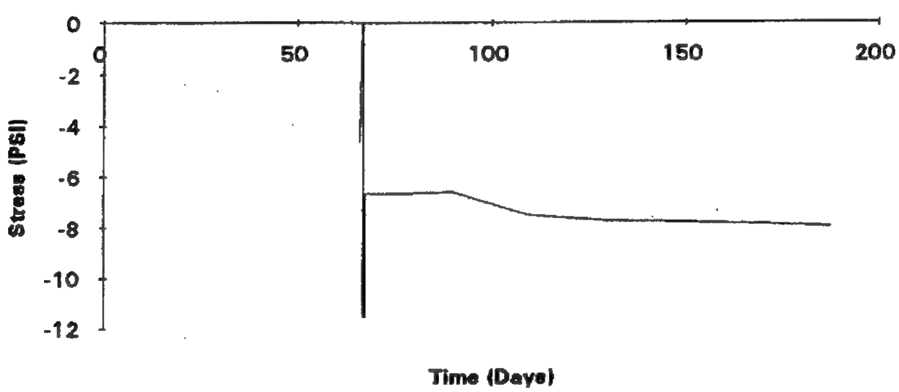
b. Stress history element 813, global Y stresses, longitudinal model

c. Stress history element 813, shear stresses, longitudinal model

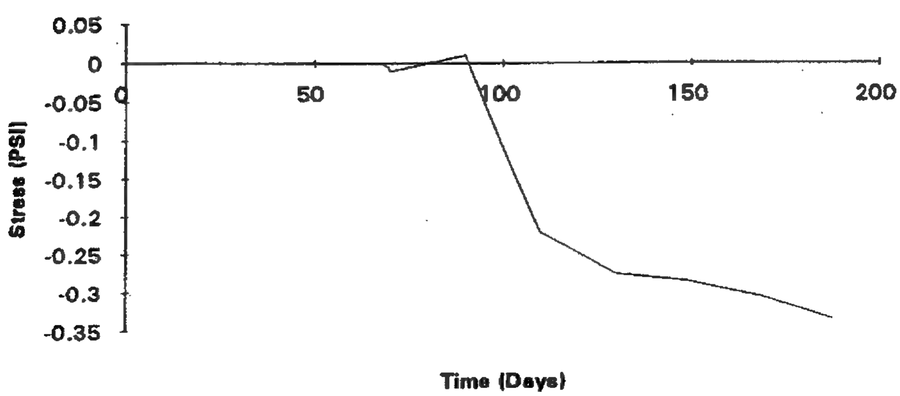
Figure 36. Stress histories for elements, longitudinal model, element 813



a. Stress history element 1364, global X stresses, longitudinal model

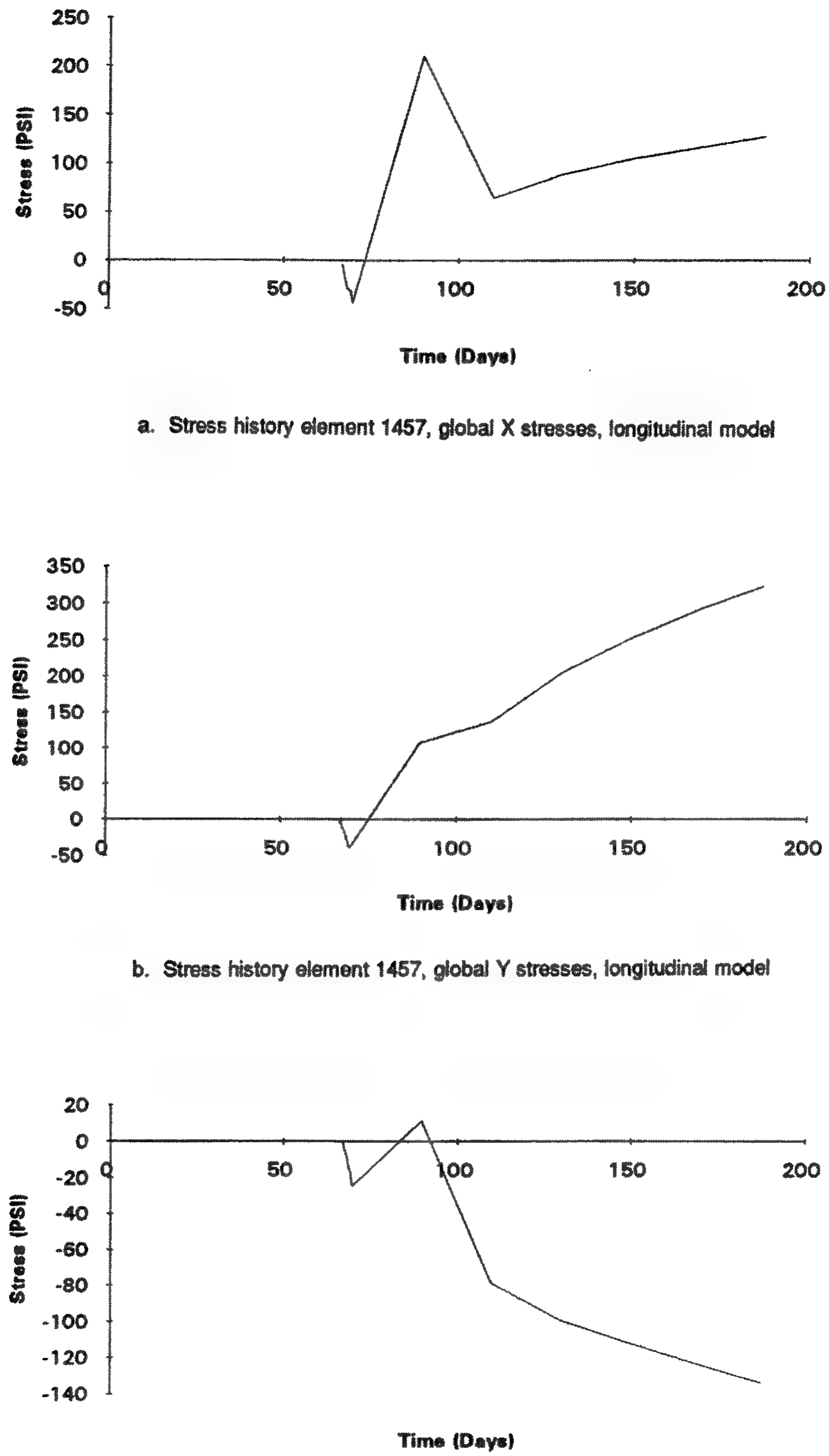


b. Stress history element 1364, global Y stresses, longitudinal model



c. Stress history element 1364, shear stresses, longitudinal model

Figure 37. Stress histories for elements, longitudinal model, element 1364



a. Stress history element 1457, global X stresses, longitudinal model

b. Stress history element 1457, global Y stresses, longitudinal model

c. Stress history element 1457, shear stresses, longitudinal model

Figure 38. Stress histories for elements, longitudinal model, element 1457

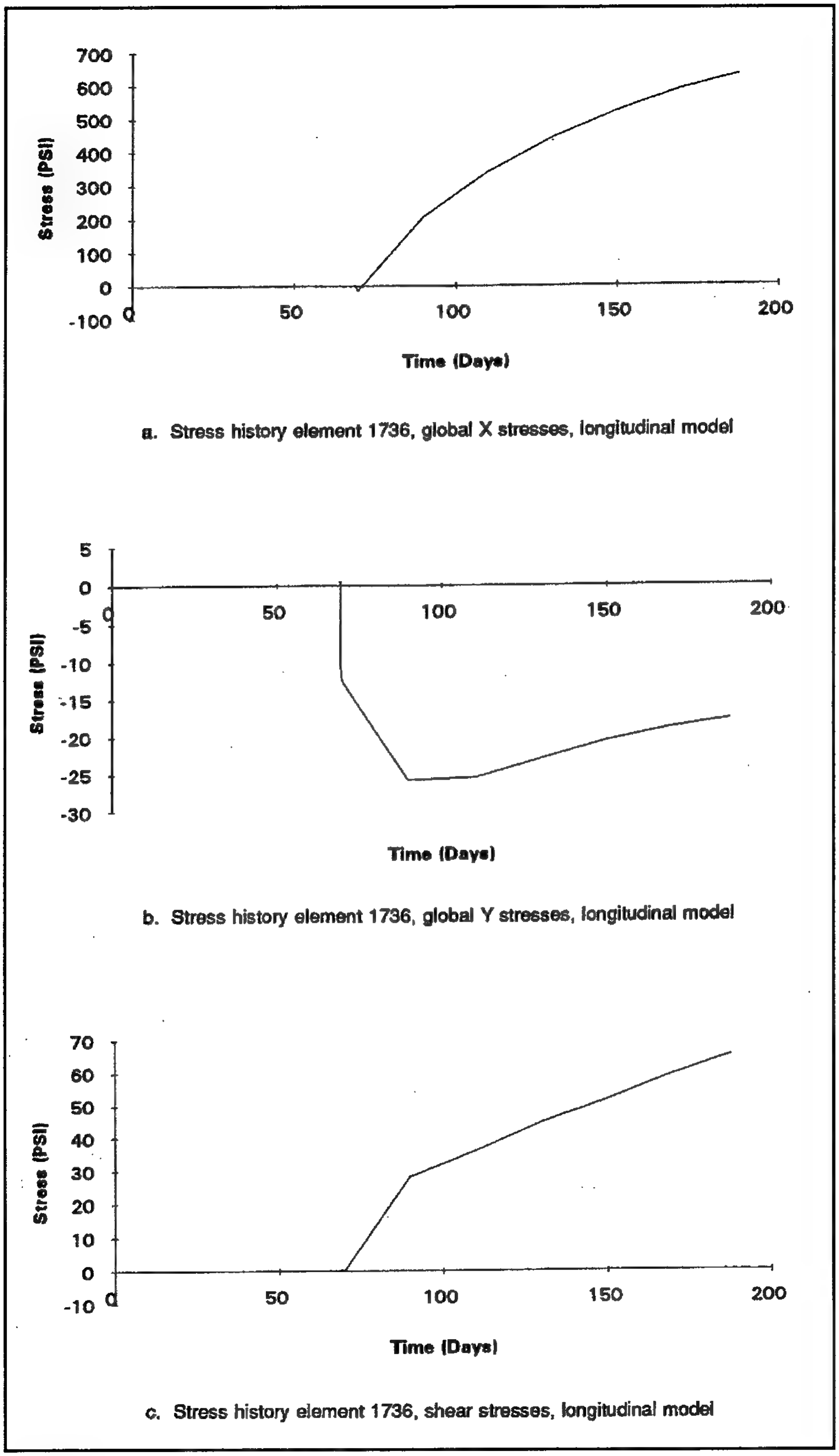
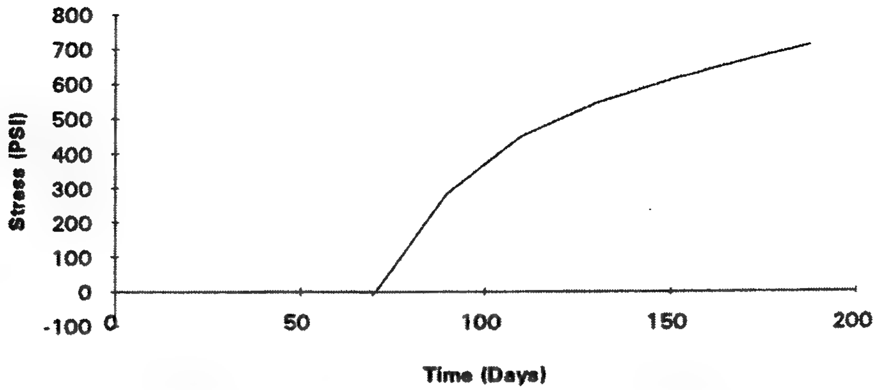
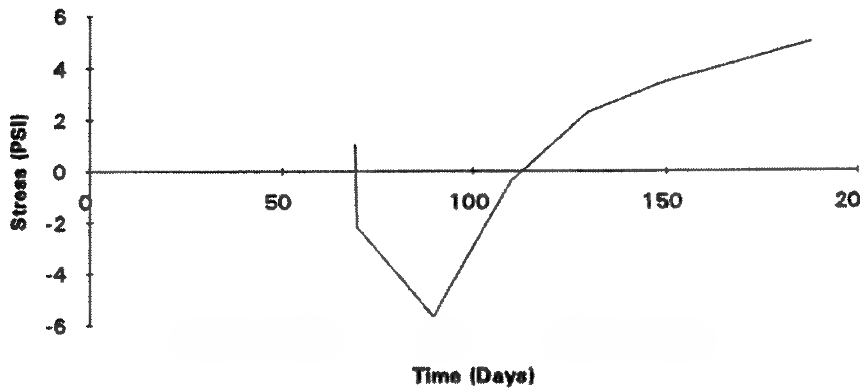


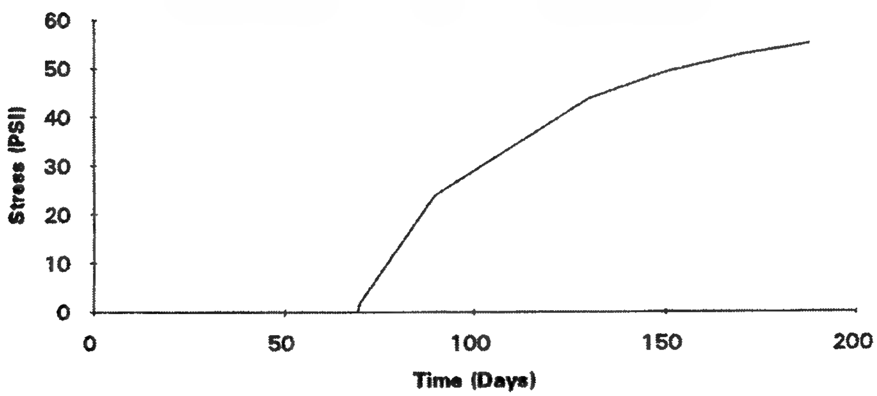
Figure 39. Stress histories for elements, longitudinal model, element 1736



a. Stress history element 1796, global X stresses, longitudinal model



b. Stress history element 1796, global Y stresses, longitudinal model



c. Stress history element 1796, shear stresses, longitudinal model

Figure 40. Stress histories for elements, longitudinal model, element 1796

Appendix A
Element Size, Parametric Study

General

The integration procedures used in the program for transient heat transfer analysis require a relationship between the minimum time step and the element size. The equation to establish this relationship is given as:

$$\Delta t > (\rho c/6k)\Delta l^2 \quad or \quad < l \sqrt{(6k\Delta t/\rho c)} \qquad \text{(A-1)}$$

where

Δt = time step

ρ = density

c = specific heat

k = thermal conductivity

Δl = element dimension

Adiabatic Heat Gain

Adiabatic heat gain in concrete begins within the first 12 hr after placement and can continue rapidly until a maximum is attained. Therefore, when performing incremental time-dependent stress analysis for concrete, it is important to keep the time steps sufficiently small during the early stages of the analysis. Input of the appropriate properties for Zintel Canyon Dam into Equation A-1 yields a maximum length of element, using a 6-hr time interval, of 27 in. Analysis for a 12-hr time interval yields a 38-in. element. A 12-hr time interval is not a good choice for calculating early heat gain in the concrete, while placing a 27-in. restriction for a 6-hr time interval doubled the size of the model. A 48-in. step height nearly matched production rates for daily concrete placements; however, it did not fit the criteria established in ABAQUS. Therefore, this study

focused on a 48- in. element size to determine its reliability in reporting temperature data.

One-Dimensional Heat Flow

This study is a simple one- dimensional heat flow problem, using material properties for Zintel Canyon Dam. Two models were generated, one with a 24- in. element size ineither direction and the other with a 48- in. element size in either direction. Depicted in Figure A 1 are the two finite element meshes and boundary conditions used for the study. One exterior row of boundary nodes was held at a constant 50 deg while the ambient surface conditions along the opposite face was a fixed 90 deg. The thermal models calculated nodal temperatures in 0.25- day increments for a period of 1 0 days. Corresponding nodal temperatures from both models were compared to determine accuracy and if stable heat gain was being generated. Figure A 2 contains plots of nodal temperatures for both the 24- and 48- in. meshes for various times. The only inconsistency was at time $t = 0.5$ day, for the 48- in. mesh, where a slight inconsistency in the heat gain exists. This can be seen in Figure A 2aFigures A 2a through A 2d indicate nearly identical heat gain, when comparing nodal temperatures at the same time steps of the two models. Because this amount of inconsistency was small, and only occurred at one time step, it was considered negligible and would not affect the outcome of the study. Therefore, a time step of 6 hr (0.25 day) and a maximum element size in any direction of 48 in. were used.

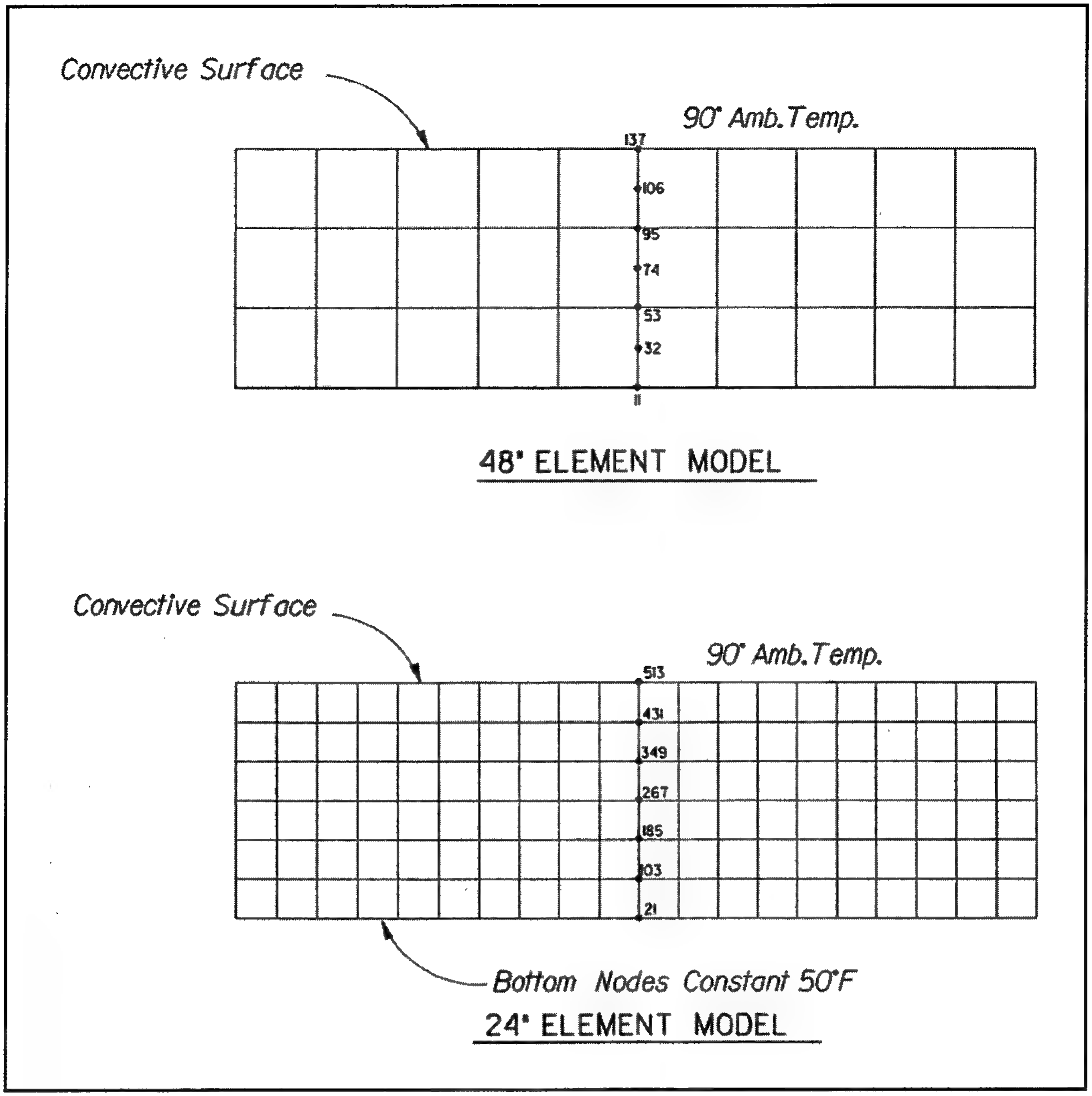


Figure A1. Finite element mesh and input data

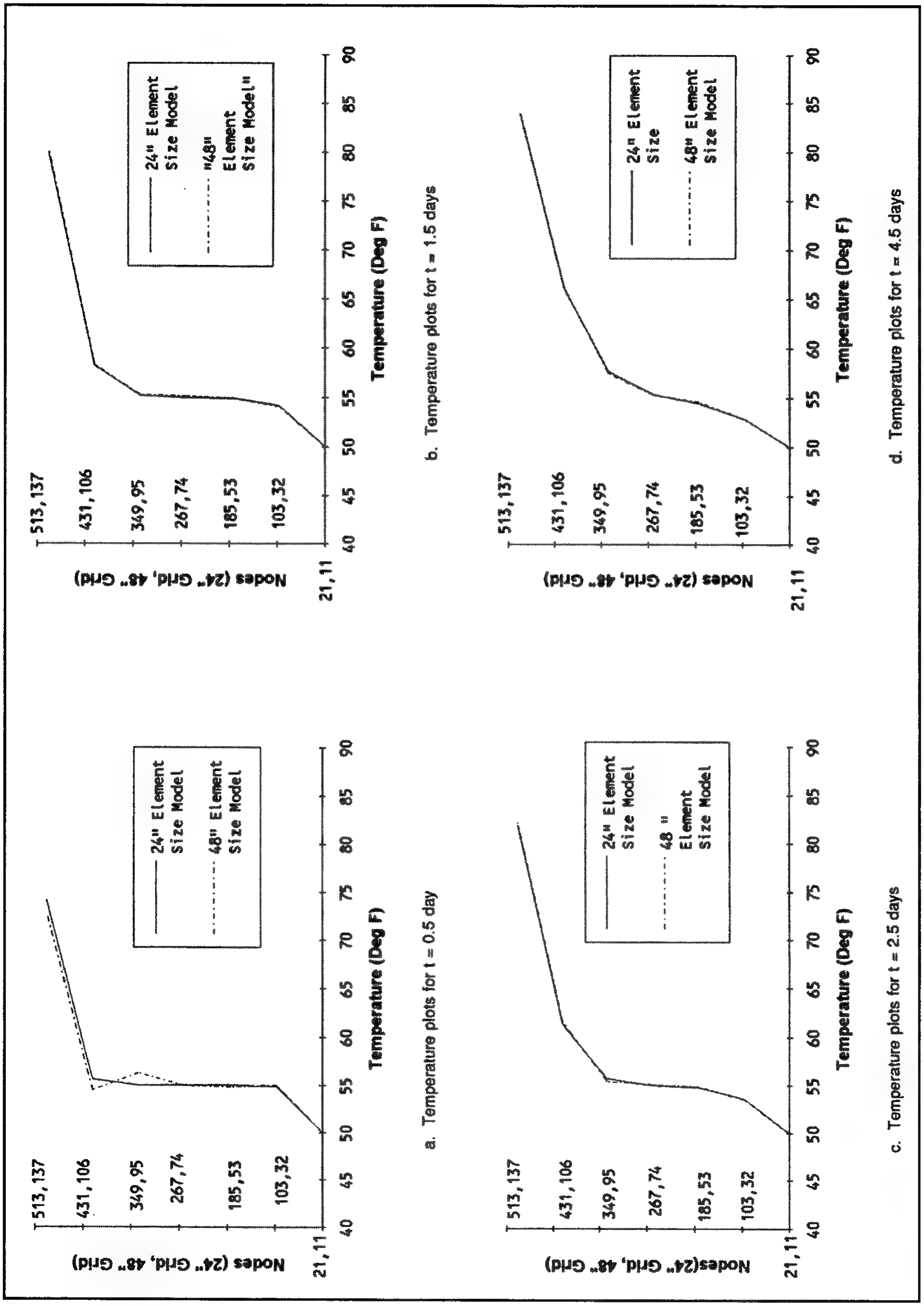


Figure A2. Temperature comparisons

Appendix B
Zintel Canyon Project

General

The Zintel Canyon Project (Figures B1 through B-4) was authorized for construction by resolution of the House and Senate Committees on Public Works, December 1970, under authority of section 201, Flood Control Act of 1965 (Public Law 298, 89 Congress). The project was constructed substantially as authorized. Detention storage was reduced from 2,560 to 1,260 acre-ft since this was considered the optimum economic size of the dam. This alternative will not prevent damages in some areas of Kennewick, WA, or avoid the use of streets as a channel during flooding in excess of 50 years (100-year thunderstorm).

Zintel Canyon Project includes a dam and a floodway channel with required structures that carry the combined flows from the dam and areas below the dam through a developed section of Kennewick, WA, to a discharge point at the Columbia River. Zintel Canyon Dam is a 90-ft retention straight axis concrete gravity structure totaling approximately 70,000 cu yd of roller compacted concrete (RCC).

The purpose of the dam is to provide flood protection to the city of Kennewick by impounding flood flows behind the dam up to the 100-year return frequency, and discharging that volume over a 20-day period. The Floodway Channel improvement consists of a buried conduit designed to pass up to a 50-year composite flood level. The 78-in. diameter buried conduit is designed to carry 400-cfs flows from its intake at West 7th Avenue and Vancouver to the outlet in the Tri-City Country Club Golf Course. From there the natural channel is designed to pass 620-cfs flows through the Burlington Northern railroad fill (Figure B1). Downstream of the railroad fill the channel is designed to provide standard project protection.

The project is co-funded by the U.S. Army Corps of Engineers (75 percent) and the city of Kennewick (25 percent). The project is located in a semi-arid region of eastern Washington and borders on the south end of Kennewick. The basin, a well defined water course called Zintel Canyon, is normally dry and drains approximately 28 square miles of the north side of the Horse Heaven Hills

of which approximately 19 square miles in area is upstream of the dam. The drainage upstream of the dam collects winterstorm and thunderstorm runoff, thereby providing a 100-year flood storage volume of 1,260 acre-ft.

Geology and Foundation

Zintel Canyon is located on the southwest flank of the Pasco Basin, a structural feature formed by downward folding and faulting of the Columbia River Basalt formation. Erosion and deposition have modified the structural features by partially filling the basin with sediments and covering the rock slope with a mantle of fine-grained materials. Bedrock is close to the surface within the drainage area of Zintel Canyon and where the dam was located. The foundation rock was composed of hard, dense basalt with closely spaced fractures. The moderately unweathered pieces were bounded by weathered fracture surfaces. Fracture fillings, particularly near the surface, were filled with silt and clay. Because the rock would easily dislodge when the joint filling dried, as well as from subsequent construction activities, the exposed foundation rock was covered with a minimum 8-in. layer of pumped concrete prior to RCC placement.

Dam, Spillway, and Outlet

The dam is a straight axis concrete gravity structure with a crest length of 520 ft and a 160-ft, centrally located, ungated overflow spillway. The height above the foundation is 126 ft and 86 ft above the existing channel with a 20-ft crest width in the nonoverflow section. The slope of the downstream face was .85 horizontal to 1 vertical to facilitate free forming of the downstream face. The upper 24 ft of the downstream face of the dam (adjacent to the spillway) was constructed using vertical concrete facing panels as was the upstream face. An 80-ft-long hydraulic jump-type stilling basin was located at the toe of the structure. This stilling basin consists of a 12-ft-thick RCC base slab integrally constructed with an RCC end sill and RCC gravity training walls. The spillway was designed to discharge a flow of 38,950 cfs. The full width of the spillway crest was surfaced with a 2-ft thickness of wet-mix shotcrete for a distance of 30 ft, until it transitions to the natural RCC surface. A fixed orifice in the intake tower regulates discharge to a maximum of 60 cfs. This discharge rate was sized to drain the reservoir in 20 days and produce minimal flows in the downstream channel. An intake tower, attached to the upstream face of the dam, provides inlet control for increasing heights of sediment deposition. The tower, a typical U.S. Soil Conservation Service design, consists of a vertical rectangular section with double weir overflow at the top of and multiple intakes along the two sides of the tower. As sediment accumulates over time against the tower, the lowest intakes, 12-in. openings spaced on 5-ft centers, are closed to prevent sediment from entering the tower and outlet system. The structure is designed to operate unmanned. Discharged water flows through a 48-in. outlet pipe cast in the RCC

dam and training wall into an impact basin. Subsequent low-velocity flows are channelized and eventually discharged into the natural channel.

Floodway Channel

A natural water course below the dam, incised into the canyon, channels water flow until it reaches the city limits where the natural channel widens out at West 7th Avenue and Vancouver. At that point the channel improvements consist of a concrete intake structure with trash racks and an earthen dike to funnel flows of 400 cfs into a buried conduit consisting of a 78-in.-diameter reinforced concrete pipe. The conduit proceeds east on West 7th Avenue then north on Rainier Street to the Tri-City golf course where it flows out from a concrete stilling well and follows a natural drainage path through the golf course. From Canal Drive, which borders the golf course on the north side, the water flows through a 6- × 8-ft concrete box culvert with a capacity of 620 cfs under Canal Drive to the Burlington Northern Railroad fill where a 78-in.-diameter steel culvert was jacked through the fill to be able to pass flows up to 620 cfs with 3 ft of freeboard on the railroad fill.

Downstream of the railroad fill, a 200-ft floodway dike was constructed to elevation 383.5 between Highway 395 fill to the high ground near the Union Pacific Railroad. An opening was left in the dike to allow train traffic to continue, with a stockpile of material nearby to fill in the opening when flow levels approach elevation 383.5. The lower Zintel Canyon water course, also known as Tweedt Canyon Drain, is a combination of natural flow channels, low bridge crossings, and culverts crossings under embankments. Depending upon flow magnitude, water will either flow completely through the area in a series of existing channels and culverts or escape the watercourse and proceed to the east of Highway 395 overpass to the Columbia River.

Construction Operations

Various phases of construction are shown in Figures B5 through B11.

Crushed basalt rock (140,000 tons) for the RCC was produced from a quarry located only a few hundred feet upstream of the dam right abutment. The quarry area was developed using a dozer (Cat D9C) and ripper. A crushing operation was set up and consisted of a primary jaw crusher, an impact crusher, and two roller crushers. The RCC mix required 29 to 32 percent of each rock product, 2.5-in. rock, 3/4-in. rock, fine aggregate, and approximately 6 percent added silt. Approximately 50 percent of the total required aggregate was produced prior to the start of RCC placement.

Design parameters require the RCC to attain a minimum compressive strength of 1,400 psi at one year of age. Static stability requires cohesion values of 35 psi at the base of the structure, and lesser values in the upper regions of the

dam. Subsequent dynamic analyses determined that lift joints also had to attain cohesion values of 50 psi in the upper regions of the structure. It was determined that the specified construction system had to provide joint quality that resulted in shear cohesion values exceeding 50 psi. The resulting mix attains a 1-year compressive strength of 2,200 psi, and displays laboratory cohesion values of 95 psi and 150 psi for unbedded and mortar-bedded lift joint configurations, respectively, at exposures of 24 hr at 70°F. The paste-to-mortar ratio is approximately 0.50, the mortar volume is 23 percent, and the workability level is approximately 15 sec, measured using the modified vebe apparatus.

Great economy is achieved when RCC production and placement can proceed uninterrupted at a consistent production rate. Repeatedly changing mix designs (e.g., for upstream and downstream richer RCC zones) creates placing problems and limits equipment selection. Consequently, only a single RCC mixture was produced for Zintel Canyon Dam, so that continual plant changes were not required. This is especially beneficial for continuous mixing operations, since there is usually no convenient method of instant and frequent mix changes. Several other mixes were used on the project. A higher cement content mix, with an air entraining admixture, was used for the top 2 ft of the stilling basin slab, as well as for the top four lifts of the dam. A low cement content mix, with an air entraining admixture, was used for the top four lifts of the training walls.

Precast panels for vertical face construction were fabricated in a commercial precast facility 100 miles from the project and then trucked to the site. The panels, 4 ft by 16 ft in width and 4 in. thick, were keyed along the horizontal joints. The panels were anchored into the RCC with 8-ft coil rods (3/4-in. diameter) and end plates. Panels were used for the vertical faces of the stilling basin training walls and for the above-grade vertical surfaces of the upstream face of the dam.

Panels were placed in a checkerboard configuration so that intermediate panels were supported by previously placed and anchored panels. This eliminated the need for external bracing. The checkerboard method of panel installation is a very economical panel system; however, tight alignment tolerances are difficult to achieve. The specified alignment tolerances were purposely broad so that such a panel installation system could be utilized.

The sloping surfaces were to be a free-formed RCC slope. In order to dress these slopes, the free slopes had to be trimmed with a backhoe bucket periodically. This produced the relatively uniform appearance of the slope and removed the uncompacted RCC on the slope.

RCC was conveyed from the plant to the placement and discharged directly into front-end loader (Cat 980) buckets. The material was driven to the specific placement location and dumped onto the uncompacted RCC surface. The dozer (Cat D4) spread the material in 14-in.-thick layers. Compaction was done with a 10-ton double drum vibrator roller (Ingersol Rand DA-50), and supplemented with a smaller roller (Ingersol Rand DH-22). Edge compaction was done with a

rammer (Wacker). Since Zintel Canyon Dam required only moderate shear performance at the lift joints, bedding mortar was applied to the lift joints to assure shear and tensile strengths, and vehicle transportation on the surface was allowed to reduce project costs. This arrangement did not jeopardize the lift joint quality and still provided significant equipment cost savings.

RCC was placed in lifts 12 in. thick and mortar was applied to each lift surface. To minimize the impacts of mortar application, the contractor formulated a system to pump mortar to the placement and shoot the mortar on the surface. The mortar mix was modified with "a high range retarder" to produce phenomenal extended set times and reasonable strength performance. This process proved to be very effective in reducing manpower dedicated to mortar placement and provided uniform coverage of mortar. The retarder is a product originally developed to delay the setting of concrete, in transit mixers, for extended periods of time.

Placement began in the key trench, with a placement of 16 lifts, totaling 1,800 cu yd. The RCC was conveyed to the placement and dropped to the rock or RCC surface by elephant trunk followed by dozer spreading and compaction. The placement area then expanded to the stilling basin slab, with 12 lifts averaging 1,400 cu yd. RCC was conveyed to loaders and subsequently transported to the placement location. Loaders traveled as much as possible on fresh RCC surfaces rather than the older surfaces that were being prepared for the next lift. Upon completion of the stilling basin slab, the placement area narrowed to 84 ft and continued to narrow as the dam's height increased. The RCC lifts for the stilling basin training walls were placed concurrently with each lift of the dam placements.

Production rates averaged 50 cu yd/hr during the early key placements and the upper lifts (in the upper section of the dam). Typical production rates of 200 to 225 cu yd/hr were maintained during placement of the stilling basin and main dam lifts. The typical placing sequence was: (1) vacuum accumulated debris, ponded water, and segregated aggregate; (2) air-clean the surface; (3) wet the surface; (4) apply bedding mortar; and (5) place the RCC.

A drilling program commenced approximately 6 months after completion of the RCC placements. The purpose of the drilling was to remove 6-in.-diameter cores from the structure and the foundation to evaluate the actual engineering properties of the RCC and the foundation rock. This testing provided excellent information for future design efforts using RCC. The testing showed that shear cohesion of the RCC lift joints more than doubled with the use of bedding mortar on the lift surfaces from 85 psi for unbedded lifts to 205 psi for bedded lift joints. The parent RCC containing no lift joint tested at 290 psi.

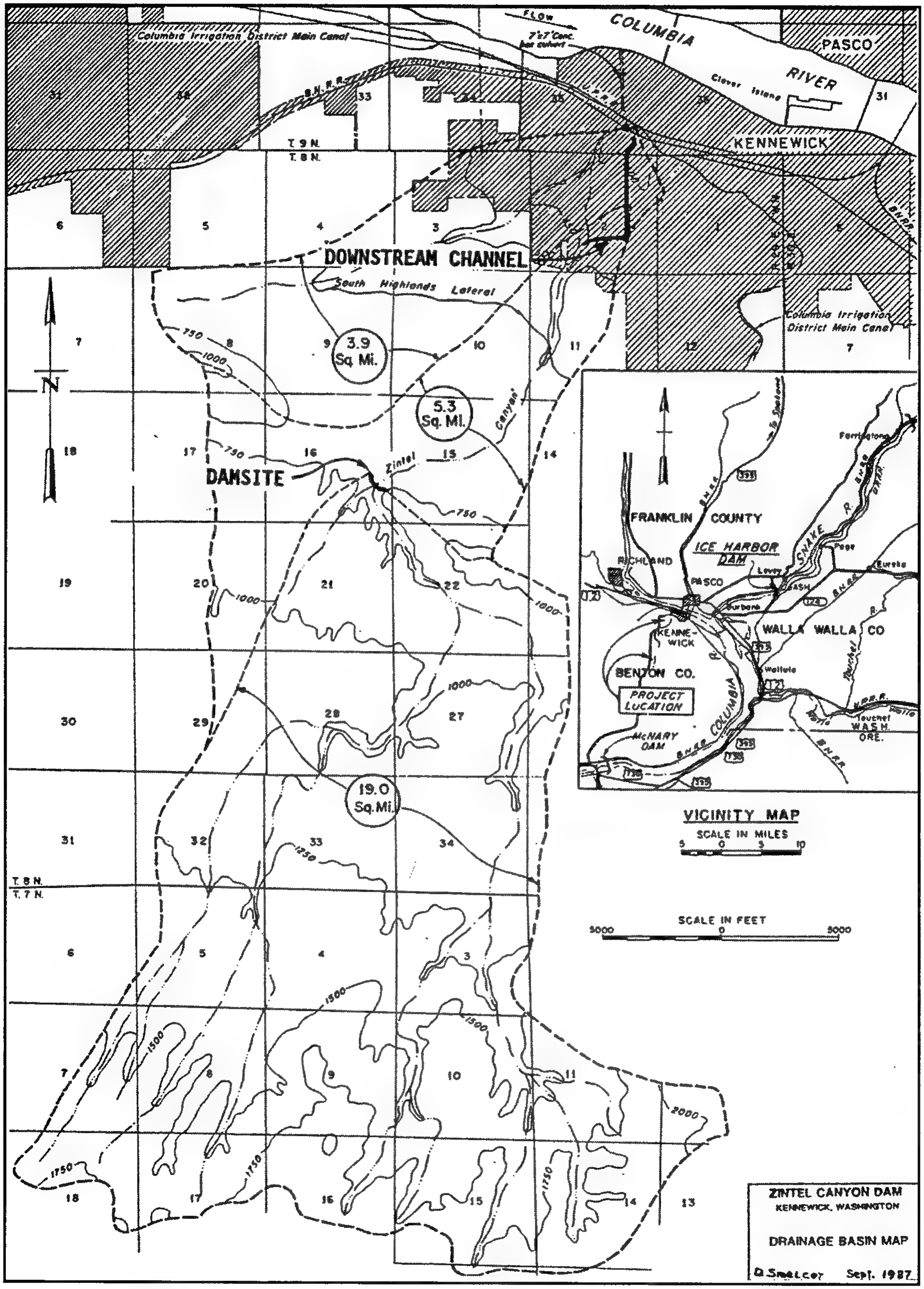


Figure B1. Basin map

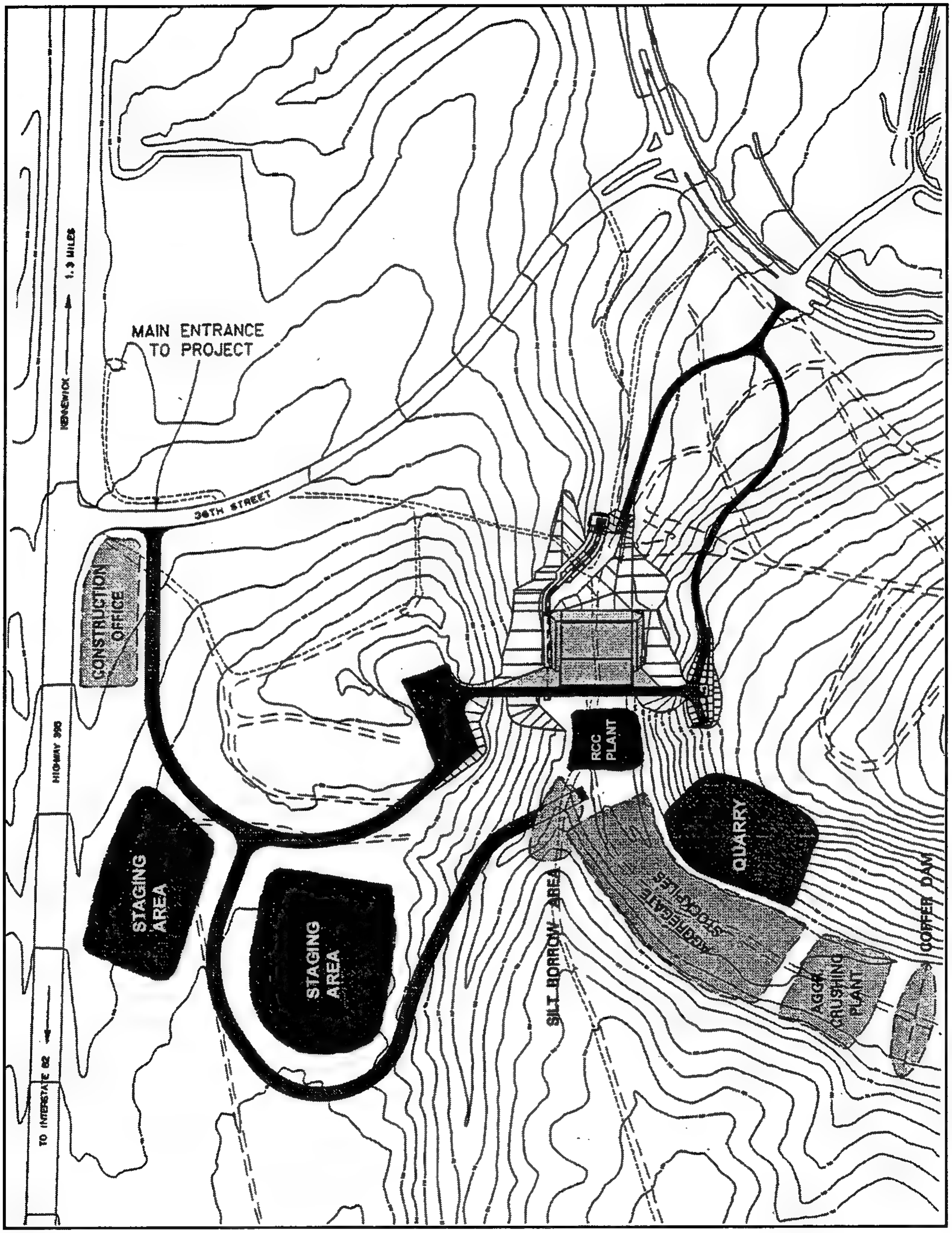


Figure B2. Site plan

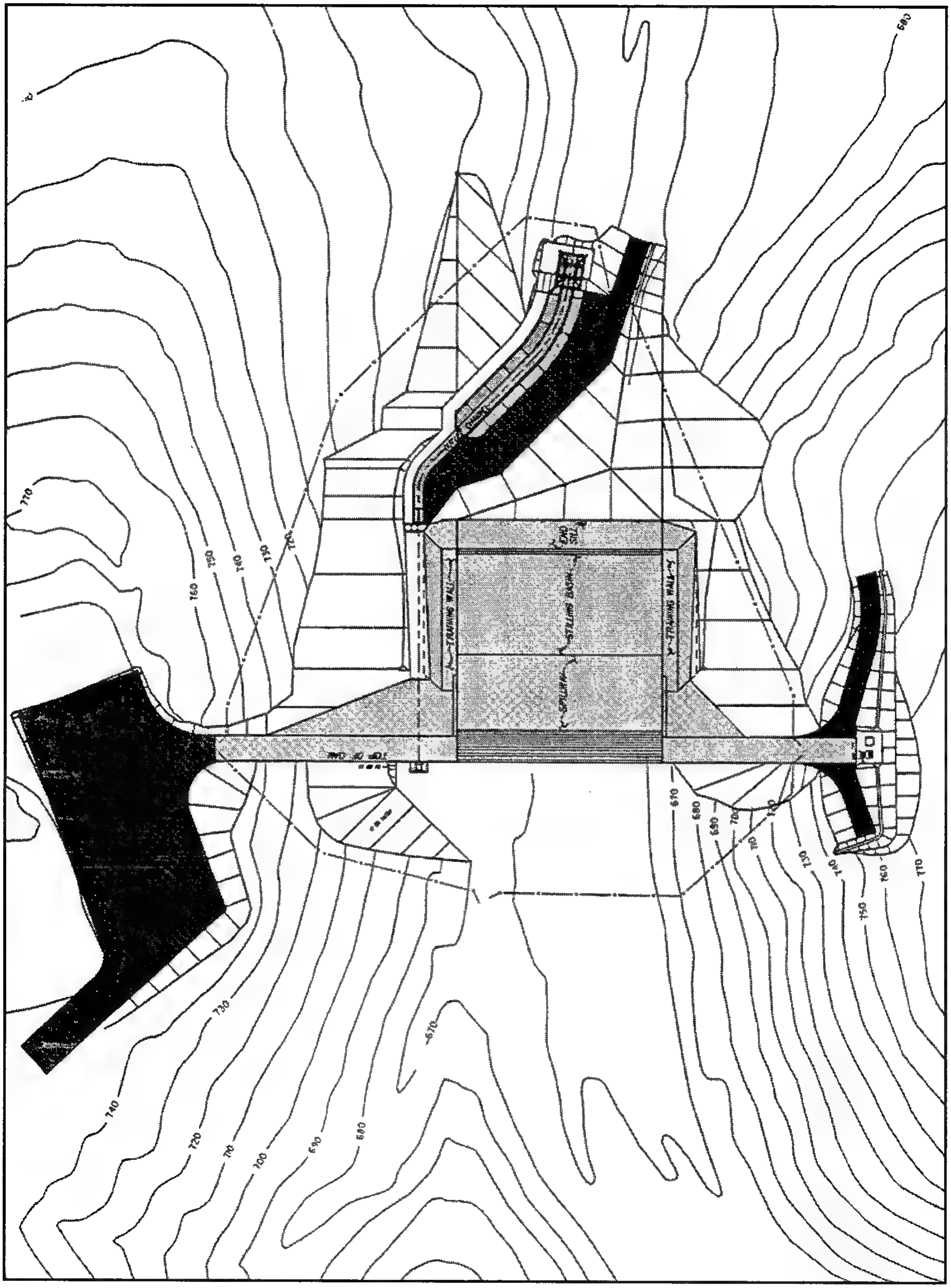


Figure B3. Dam plan

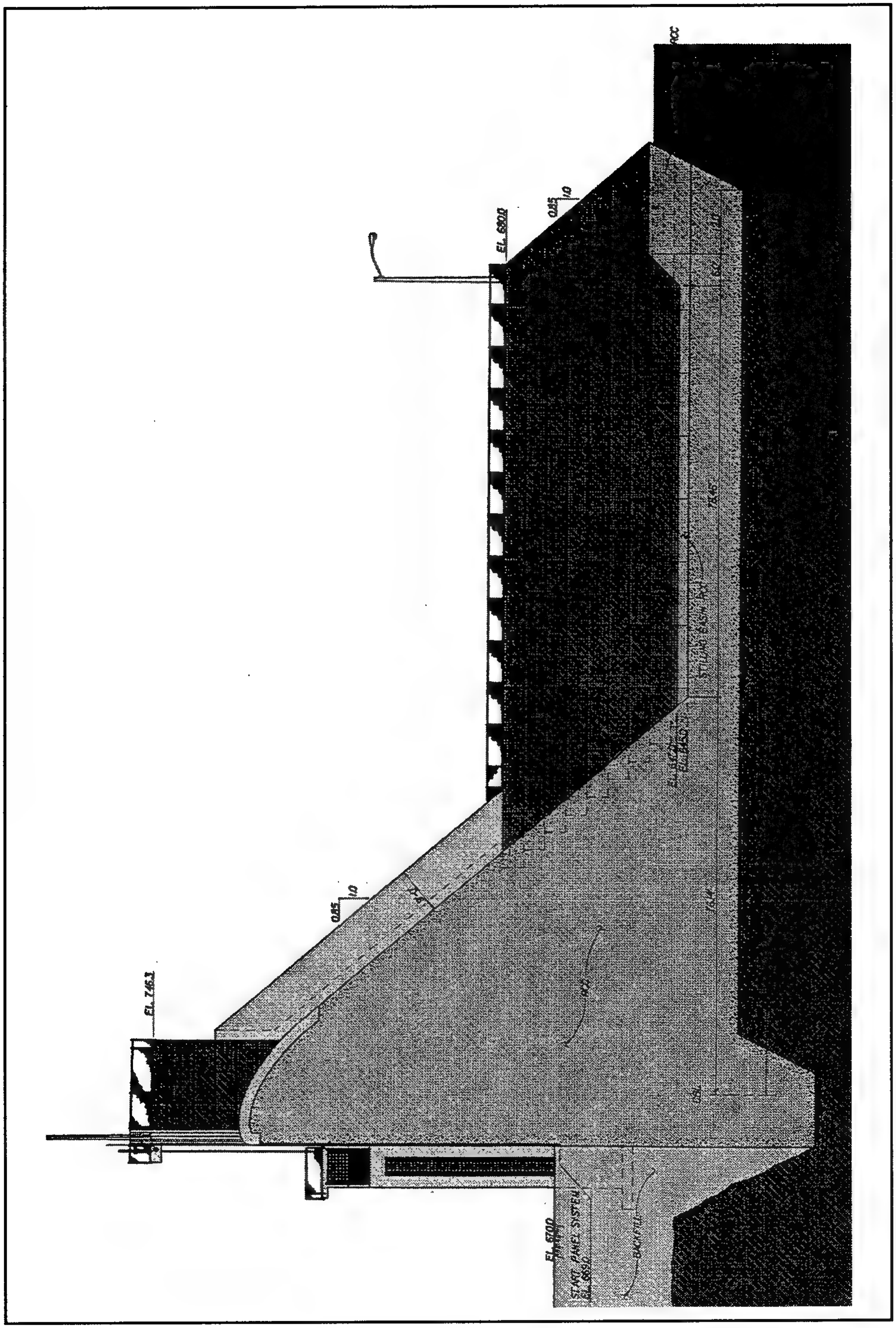


Figure B4. Dam section

Figure B5. Excavating basalt rock foundation for dam

Figure B6. Foundation after placement of concrete and shotcrete

Figure B7. Transportation, spreading, and compacting RCC

Figure B8. Placing RCC lifts at elevation above the top of the training wall

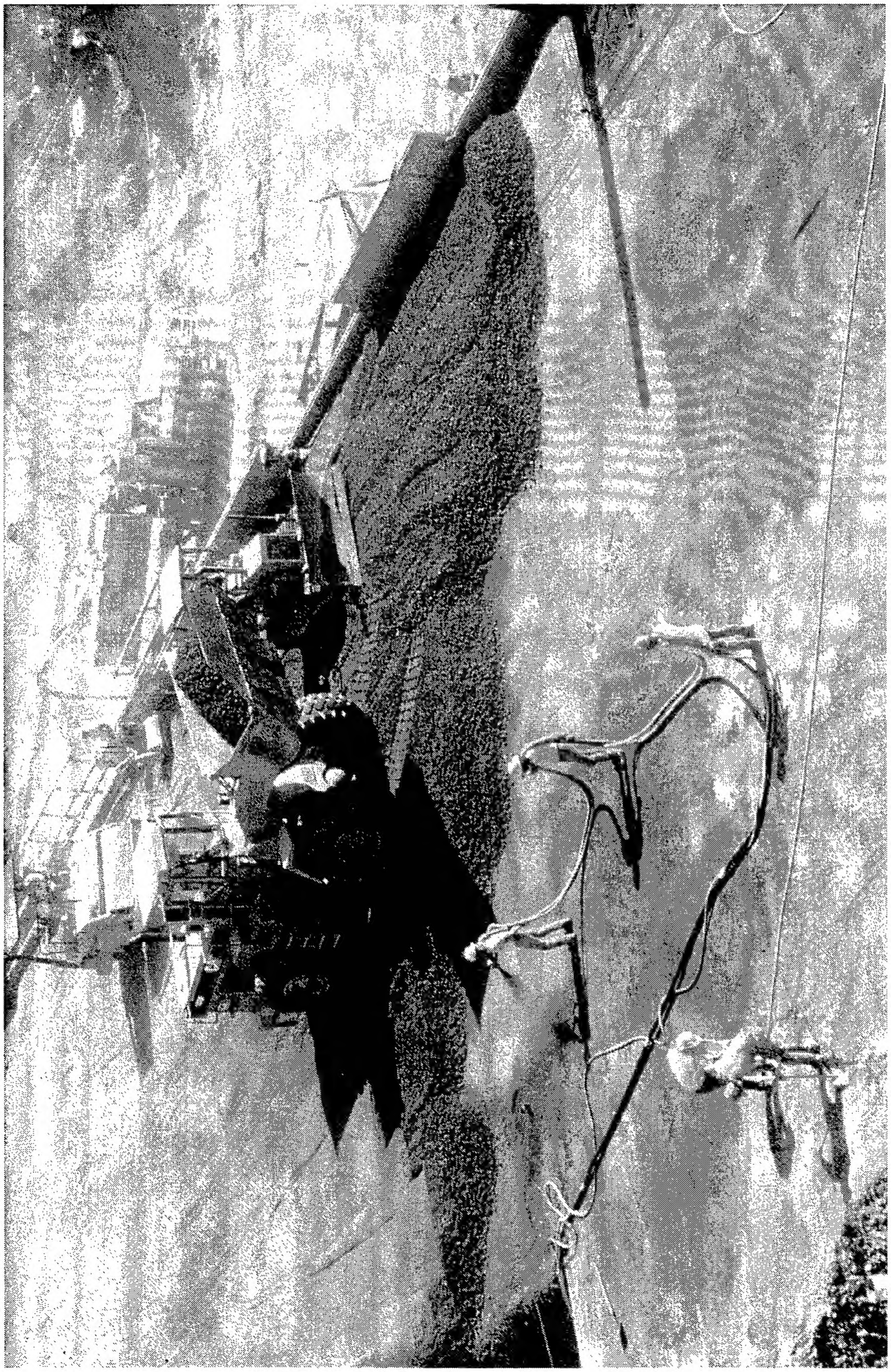


Figure B9. Typical RCC placement process of loader transport

Figure B10. Constricted placement conditions for RCC placement

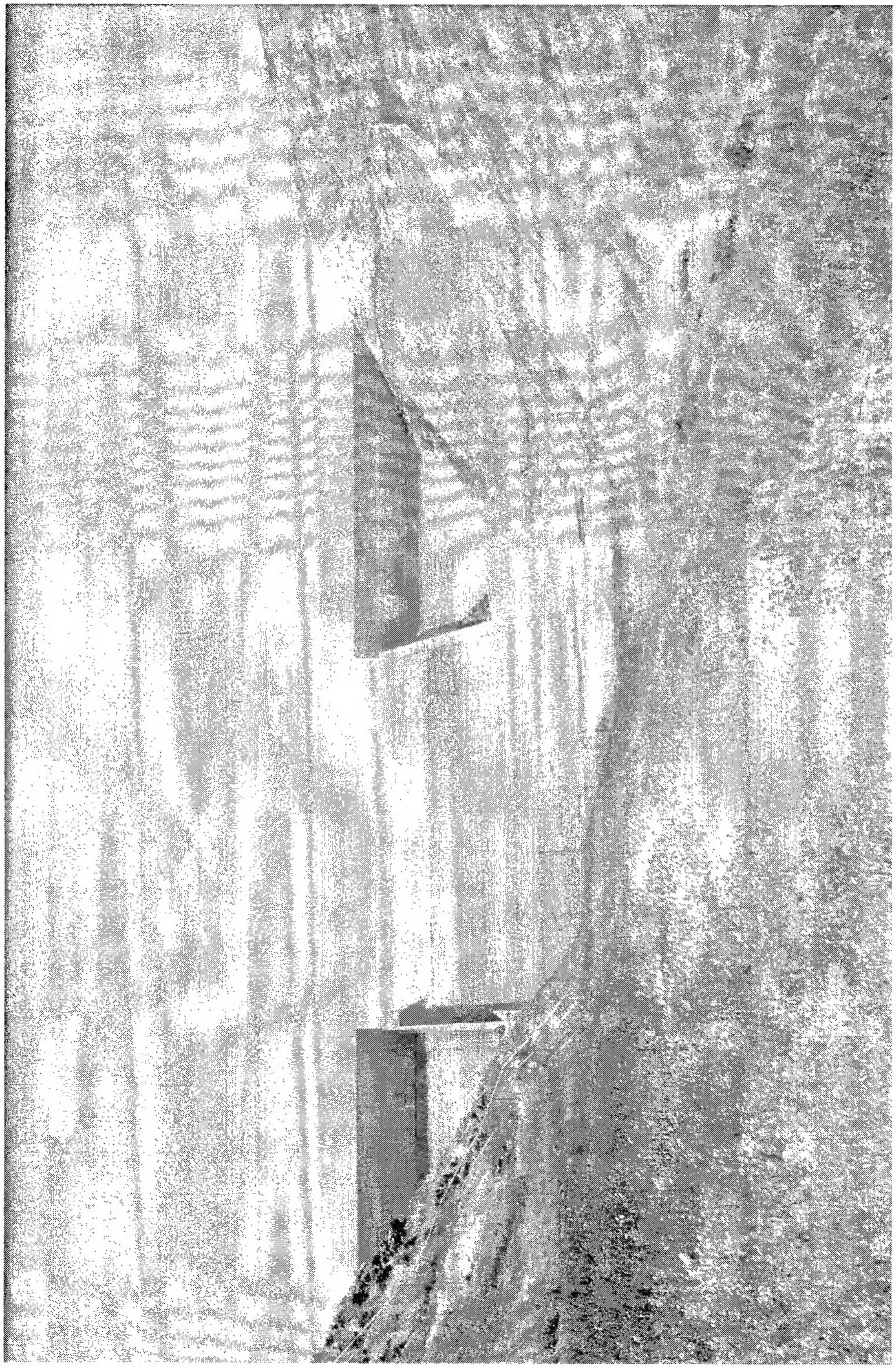


Figure B11. View of the completed Zintel Canyon dam

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

This paper presents the time-history thermal analysis of Zintel Canyon Dam, a structure of approximately 70,000 cubic yards of roller compacted concrete (RCC). This study was initiated to demonstrate the implementation of the superseded ETL 1110-2-324, "Special Design Provisions for Massive Concrete Structures," as applied to RCC structures. The results of the study were published in ETL 1110-2-536, dated December 31, 1994, which should be used as guidance when conducting analyses of mass RCC structures. Since construction of the dam has been completed, actual data for ambient conditions, placing conditions, and available material properties were used in the analysis.

Time-dependent material properties were incorporated into the analysis using specially developed user subroutines for ABAQUS, a general purpose finite element code. The analysis showed that several locations in the structure exhibit high stress levels capable of generating thermal cracks. Initiation of cracks in the RCC, parallel to the axis of the structure, was evident in the results; however, stress levels were not of a magnitude to propagate these cracks to the point of concern. In addition, stress results indicated that transverse cracking of the structure may occur at up to three locations. The performance predicted by the analysis was very similar to the thermal performance predicted by earlier manual computations.

15. SUBJECT TERMS

adiabatic temperature rise, concrete, cracking, dams, finite element method, joints, mass concrete, mass gradient, restraint, roller compacted concrete, surface gradient, temperature, tensile strain capacity, thermal analysis, thermal strain, thermal stress, Zintel Canyon Dam

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